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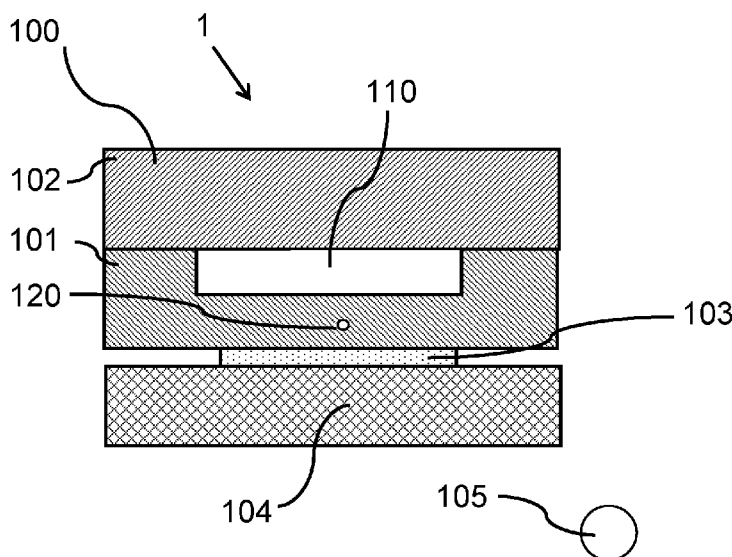


Figure 1

(57) Abstract: A manufacturing apparatus comprising: a material-handling manufacturing tool comprising a first tool part defining at least partially a chamber for holding or conveying a material during a manufacturing process; at least one Peltier module in thermal contact with the first tool part that is configured to provide temperature control of the tool part by electrically controlled heating and/or cooling; and an electronic controller configured to operate each Peltier module present; wherein the electronic controller is arranged to derive a measurement indicative of the heat flow through one or more of the Peltier modules.



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MANUFACTURING APPARATUS

The present disclosure relates to a manufacturing apparatus, in particular a manufacturing apparatus comprising a material-handling tool such as a material-handling manufacturing tool for forming a part by a process involving heating and/or cooling one or more materials. The present disclosure relates to uses of a manufacturing apparatus comprising a material-handling manufacturing tool and methods of manufacture employing a manufacturing apparatus comprising a material-handling manufacturing tool.

Fabricating plastics, polymer parts or composites can be done by moulding methods such as injection moulding or compression moulding. Such processes may incorporate heating and cooling within a mould with the application of pressure to form the desired polymer part. Heating may be used to improve flow of the polymer in order to fully fill the mould. Cooling may be used to achieve the correct material properties and speed up production. Conventional moulds may typically use heating and/or cooling fluids, e.g. air, and/or electrical heating.

A potentially more energy efficient and/or rapid method to heat and cool a mould is to use a thermoelectric or Peltier module that can pump heat in either direction depending on the direction of the supplied current flow, so is well suited to heating and cooling cycles.

US3804362A discloses a Peltier module between two thermally insulated mould sections that can offer rapid cooling and temperature control through Peltier module electronic control.

US2003015308A1 discloses a Peltier module configured to superheat a region of one or both dies proximate to a hard-to-fill region of a molding cavity prior to and during filling of the molding cavity with a fluid material. The fluid material has a composition selected to form a ceramic core or a fugitive pattern.

WO2007121934A1 discloses multiple Peltier modules and temperature sensors in a polymer processing system. WO2007121934A1 discloses that problems of filling thin long walls can be solved by overheating some surfaces.

WO2014135858A1 discloses use of a fluid stream (typically air) at variable rates throughout a mould to provide regional control of temperature within the mould. This may allow for improved temperature uniformity, allowing improved control of viscosity of the filling material. This can allow reduced wall thicknesses of parts (lighter components), elimination of weld lines/sink marks and aggressive adjacent section thickness changes.

WO2011048365 discloses that zonal temperature control in a mould can be used to control the material properties of the part, for example by controlling cooling rates to control crystallinity in a thermoplastic.

While zonal temperature control allows more detailed control of the mould temperature profile and thus the polymer part, the required temperature profiles needed to provide the correct properties across the polymer part are not simple to predict. It may require detailed modelling, difficult in-tool measurements or subsequent analysis of multiple areas on the formed part, requiring multiple iterations.

Differential scanning calorimetry (DSC) is commonly used in the characterisation of polymers, to measure how a material's heat capacity changes with temperature. For example in semi-crystalline thermoplastics (e.g. polyethylene terephthalate (PET), nylon, polyethylene, polypropylene, fluoro polymers, polyethersulfone (PES), polyether ether ketone (PEEK)), DSC can be used to calculate the crystallinity of the polymer. The crystallinity can influence the brittleness, toughness, stiffness or modulus, optical clarity, creep or cold flow, barrier resistance (ability to prevent gas transfer in or out) and long term stability, so is an important parameter to be determined. In addition, DSC can provide information on polymer glass temperatures, and give information on impurities such as mould lubricant contamination or variations in plastic composition. At present, DSC is performed after production of the polymer part on small samples taken from the formed polymer part.

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It would be beneficial to overcome or at least mitigate one or more of the problems associated with the prior art.

A first aspect provides a manufacturing apparatus comprising:

a material-handling manufacturing tool comprising a first tool part defining at least partially a chamber for holding or conveying a material during a manufacturing process;

at least one Peltier module in thermal contact with the first tool part that is
5 configured to provide temperature control of the tool part(s) by electrically controlled heating and/or cooling; and

an electronic controller configured to operate each Peltier module present; wherein the electronic controller is arranged to derive a measurement indicative of the heat flow through one or more of the Peltier modules.

10

The term material-handling manufacturing tool may be understood to refer to any tool used to hold or convey a material during a manufacturing process, e.g. a manufacturing process for forming a part by a process involving heating and/or cooling one or more materials. An example of a material-handling manufacturing tool
15 may include: a moulding tool; a die such as an injection die or an extrusion die; a pipe or a tube for conveying a material during a manufacturing process; or a storage vessel.

The first Peltier module may be in thermal contact with a first thermal buffer.

20 The material-handling manufacturing tool may comprise one or more further tool parts, e.g. a second tool part. Together, the tool part(s) may define at least partially a chamber for holding or conveying a material during a manufacturing process.

At least one Peltier module may be in thermal contact with each further tool part.

25

One or more of the Peltier modules, e.g. each Peltier module, may be in thermal contact with a thermal buffer.

The material-handling manufacturing tool may comprise a moulding tool.

30

The moulding tool may comprise a first mould part configured to at least partially define a mould cavity having a shape, the shape of the mould cavity defining the shape of a part to be moulded.

The moulding tool may comprise one or more further mould parts. Together, the mould parts may at least partially define the mould cavity.

For example, the moulding tool may comprise a second mould part. The first and
5 second mould parts may at least partially define the mould cavity.

In another example implementation, the moulding tool may comprise three or more mould parts.

10 The manufacturing apparatus may comprise at least one Peltier module in thermal contact with the second mould part and a second thermal buffer. The manufacturing apparatus may comprise at least one Peltier module in thermal contact with each tool part, e.g. each mould part, present.

15 The manufacturing apparatus may comprise a plurality of Peltier modules in thermal contact with the first tool part. Each Peltier module in thermal contact with the first tool part may be in thermal contact with the same thermal buffer, or two or more individual thermal buffers.

20 The manufacturing apparatus may comprise a plurality of Peltier modules in thermal contact with the second tool part. Each Peltier module in thermal contact with the second tool part may be in thermal contact with the same thermal buffer, or two or more individual thermal buffers.

25 Advantageously, the or each Peltier module may provide a means for heating and/or cooling at least a portion of one or more tool parts.

The manufacturing apparatus may comprise at least one temperature sensor. At least one temperature sensor may be disposed near, on or at least partially within the first
30 tool part. At least one temperature sensor may be disposed near, on or at least partially within the second tool part. Any suitable number of temperature sensors may be present.

Measurement of the heat flow through the Peltier module may be derived from a
35 measurement of at least two of the current, voltage or electrical power supplied to the

Peltier module. This heat flow measurement as the temperature changes may provide similar information to a differential scanning calorimetry (DSC) measurement, thereby enabling in-tool DSC measurements.

- 5 Each tool part may comprise any suitable shape. The chamber, e.g. mould cavity, may comprise any suitable shape. The mould cavity may comprise a substantially sealed internal volume encompassed at least partially by the first mould part and any further mould part(s).
- 10 The first tool part may be connectable to and detachable from any further tool part(s). When connected, the tool parts may form the chamber, e.g. the moulding cavity.

- In use, one or more of the Peltier modules may be powered to act as a heat pump. When operated as a heat pump the Peltier module(s) may pump heat from the or a first thermal buffer to the first tool part, heating up the first tool part. The electronic controller may be configured to receive feedback from one or more temperature sensors and to adjust the power and/or current and/or voltage to at least one of the Peltier modules based on the difference between a measured temperature and a desired temperature, for example using a thermostatic controller, a pulse width modulation (PWM) controller, and/or a proportional–integral–derivative controller.
- 15
- 20

- The electronic controller may be programmable with one or more pre-determined desired temperatures. The electronic controller may comprise a memory operable to store one or more desired temperatures. The electronic controller may be configured such that a user may adjust one or more pre-determined desired temperatures.
- 25

- A volume of material may then be introduced into the chamber, e.g. the mould cavity. The material may comprise a polymer that has been heated to a fluid state. The material may be introduced into the chamber by any suitable means.
- 30

- As polymer flows and/or packs into the chamber, the first Peltier module power and current direction may be controlled and/or adjusted to provide heating or cooling of the first tool part. Feedback from at least one temperature sensor to the electronic controller may be used to control and/or adjust the heating or cooling provided by at least one Peltier module. The electronic controller may control at least one Peltier
- 35

module such that the temperature of any tool part remains constant or within a prescribed temperature range. The electronic controller may control at least one Peltier module such that the temperature of any tool part increases or decreases to a desired temperature.

5

For instance, once the moulding tool is filled with a volume of material, such as a polymer, the first Peltier module may be powered with a current direction opposite to when the Peltier module was acting as a heat pump in order to provide controlled cooling of the first mould part. In this way, heat may be pumped into the or a first thermal buffer. Feedback from the at least one temperature sensor to the electronic controller may be used to control and/or adjust the rate of cooling or temperature reduction provided by the first Peltier module.

Cooling of the first mould part may allow for more control over the rate of cooling of the material contained within the mould cavity. In this way, the properties of the finished part may be more easily controlled. Once the part has sufficiently cooled, the part may be ejected, for example, by separation of the first and second mould parts. The first and second mould parts may then be reconnected and the moulding of another part may begin.

20

Advantageously, efficiency gains over known heating and cooling methods may be achieved as the Peltier module(s) is/are pumping heat to and from the thermal buffer(s). In addition, utilising one or more Peltier modules may increase the temperature ramp rates, reducing the time taken to make each part, increasing manufacturing speed.

25

The in-tool DSC or heat flow measurement may be performed as the material, e.g. the polymer, sets or solidifies.

The voltage, V , and current, I , through a Peltier module is related by the expression given in Equation 1 below:

$$V = I * R - \alpha * \Delta T \quad -(1)$$

where R is the electrical resistance of the Peltier module, α is the effective absolute Seebeck coefficient of the Peltier module and ΔT is the temperature difference across the Peltier module, i.e. the tool part temperature minus the thermal buffer temperature.

35

I is defined such that a positive I results in tool part cooling. R and α are weak functions of temperature so can be assumed constant or corrected for with the known temperature dependent material properties, so that ΔT can be directly calculated with a measurement of V and I of the Peltier module. Since the electrical power to the Peltier module is the product of I and V , then a measurement of the electrical power can be substituted for a measurement of one of I or V . If the temperature difference across the module, ΔT is known, then the heat flow out of the tool part, Q , can be calculated by Equation 2:

$$Q = \Delta T / R_{th} + \alpha * I * T_M - 0.5 * I^2 * R \quad -(2)$$

where R_{th} is the thermal resistance of the Peltier module with no current flow and T_M is the tool part temperature.

The electronic controller may be configured to measure any one or more of the voltage and/or the current through the Peltier module and may be configured to also receive data from the temperature sensor(s).

Therefore, in some embodiments the voltage and current through the Peltier module may be measured to enable a calculation of the heat flow. The heat flow may be analysed directly or converted into a combined heat capacity of the moulding tool and polymer part by dividing the heat flow by the rate of change of the moulding tool temperature.

The combined heat capacity of the moulding tool and polymer part may optionally be divided by the mass of the moulding tool and polymer part to give the combined specific heat capacity of the moulding tool and polymer part. The combined heat capacity of the moulding tool and polymer part may optionally have the known heat capacity of the moulding tool subtracted from it to give the polymer part heat capacity. The polymer part heat capacity may optionally be divided by the mass of the polymer part to give the polymer part specific heat capacity.

30

The Peltier module may be configured to provide the temperature control by electrically controlled heating and/or cooling of the tool part(s) where the Peltier module power control depends on feedback from the at least one temperature sensor.

The Peltier module power control may be fixed during a heat flow measurement, for example using a fixed input voltage or fixed duty cycle if PWM control is used and measuring how the current changes or fixing the current input and measuring how the voltage changes.

5

At least one Peltier module may be electrically driven in a constant state during a heat flow measurement.

10

The power control of at least one Peltier module may be operable to be fixed at one or more pre-determined values. The power control may be fixed at a value to achieve maximum cooling rate. The power control may be fixed at a value to achieve maximum heating rate.

15

The power control may be fixed only around the temperature points where the most sensitive measurements are required, for example around the crystallisation temperature of a semi-crystalline polymer. The pre-determined fixed values of the power control may be variable depending on the material that is to be handled, e.g. moulded.

20

At least one Peltier module may be unpowered when taking one or more heat flow measurements. At least one Peltier module may be unpowered when taking the most sensitive heat flow measurements. At least one Peltier module may be unpowered when taking one or more heat flow measurements where a measured or calculated temperature is within a pre-determined range. The pre-determined range may be approximately around the crystallisation temperature of a semi-crystalline polymer that is to be moulded.

25

When the Peltier module is unpowered, equations 1 and 2 may be simplified to:

$$V_{oc} = -\alpha \Delta T \quad -(3)$$

30

$$Q_{oc} = \Delta T / R_{th} . \quad -(4)$$

Where V_{oc} is the open circuit voltage, the voltage across the Peltier module with zero current and Q_{oc} is the heat flow through the Peltier module when zero current is applied to the Peltier module. A measurement of V_{oc} can therefore be used to measure the heat flow Q_{oc} . This method may also eliminate the requirement to know R and so will increase the sensitivity of the heat flow measurement.

35

The Peltier module may only be unpowered in order to measure V_{oc} for the duration of time to take the most sensitive measurements. The Peltier module may only be unpowered for one or more short durations, for example to periodically measure V_{oc} and thus sample the temperature difference and heat flow across the Peltier module. In this way, the duration of the time that the Peltier module is turned off, therefore reducing the heat flow, is minimised. By minimising the time the Peltier module is turned off, the cooling time will be minimised. In this way, the short cycle times that are desired for high-speed production may be achieved.

10 The manufacturing apparatus may comprise a first Peltier module that is configured to provide temperature control of the tool parts by electrically controlled heating and/or cooling and may further comprise a second Peltier module where the second Peltier module is configured to act as a measurement Peltier module for measuring heat flow through the second Peltier module. The second Peltier module may be unpowered. The open circuit voltage of the second Peltier module may be monitored to determine the heat flow for the in-tool DSC measurement.

The second Peltier module may be smaller than the first Peltier module to reduce the loss in cooling and heating control while still maintaining the more sensitive monitoring of an unpowered Peltier module. The second Peltier module may have at least five times fewer thermoelectric elements than the first thermoelectric module, to reduce the impact on cooling and heating control. The second Peltier module may have at least five times less thermoelectric material area arranged perpendicular to the heat flow than the first Peltier module.

25 The first and second Peltier modules may be integrated so that the first and second Peltier module may share the same substrates but be electrically isolated from each other. The first and second Peltier modules may be integrated together into one single Peltier module with dual tracks having two separate continuous electrical series circuits controlling different areas of thermoelectric elements within the Peltier modules. This may simplify assembly and reduce any temperature gradients in the mould due to differences in heat flow in the first and second Peltier modules,

35 Measurement of the heat flow may be performed by the measurement of the open circuit voltage of a second independent electrical track on at least one Peltier module.

In this way, an increase in measurement sensitivity from measuring the Peltier module in an unpowered state (i.e. measuring V_{oc}) can be achieved without increasing the number of Peltier modules.

- 5 The material-handling manufacturing tool, e.g. the moulding tool, may be described as comprising a plurality of thermal zones, where each thermal zone is associated with at least one Peltier module. In this way, the material-handling manufacturing tool, e.g. the moulding tool, may comprise a plurality of thermal zones and the manufacturing apparatus may comprise a plurality of Peltier modules. The manufacturing apparatus
- 10 may comprise an independent temperature sensor for each thermal zone. By utilising multiple temperature sensors and multiple Peltier modules, different thermal zones of the mould can be defined, e.g. with one temperature sensor and one Peltier module per thermal zone.
- 15 Each thermal zone may be independently thermally controlled, with Peltier modules in different thermal zones electrically driven in different ways depending on their corresponding temperature sensor reading and the desired temperature for that thermal zone. Such independent zonal control of temperature allows potential improved temperature uniformity. For example, extra heating may be applied to parts of the
- 20 material-handling manufacturing tool, e.g. the moulding tool, that have additional cooling losses.

Advantageously, this can allow improved control of viscosity of the material, e.g. improving filling of the mould cavity. This can allow reduced wall thicknesses of

25 parts (lighter components), elimination of weld lines/sink marks, aggressive adjacent section thickness changes. In addition, this can reduce press clamp, fill and closure pressures, because the input material temperature profile is no longer driven by the coldest, thinnest portion of the mould cavity. In addition, controlling cooling rates to be uniform across the mould can reduce thermal stresses and subsequent deformation

30 of parts. As well as allowing increased thermal uniformity, zonal thermal control allows deliberate, advantageous non-uniformities to be generated, for example increasing temperature in some areas of the mould, especially thinner parts, to promote filling of these difficult to fill parts of the mould.

Each independently controlled thermal zone may have more than one Peltier module associated therewith.

Each independently controlled thermal zone may have more than one temperature
5 sensor associated therewith.

To increase heating ramp rates, additional electrical heating may be applied to the material-handling manufacturing tool, e.g. the moulding tool.

10 The thermal buffer may be actively heated or cooled prior to or during the manufacturing process, e.g. the moulding process. Advantageously, this may increase heating and cooling ramp rates.

One or more of the thermal buffers may comprise a heat exchanger. One or more of
15 the thermal buffers may comprise a heat sink. One or more of the thermal buffers may comprise a heat sink with a fan or a blower. One or more of the thermal buffers may be split into multiple parts.

A multiplexer may be used in the measurement of the temperature of the tool part(s)
20 by the temperature sensor(s). A multiplexer may be used in the measurement of the heat flow through the Peltier module(s).

One or more of the temperature sensors may be disposed on or at least partially in one of the thermal buffers. The temperature of the tool part may be calculated using the
25 temperature of the thermal buffer and the temperature difference across the Peltier module (for example calculated from equation 1 or 3 depending on measurement method).

The manufacturing apparatus may be arranged to provide any number of thermal
30 zones.

One or more thermal zones may be formed on both the first tool part and the second tool part.

The manufacturing apparatus may comprise at least four Peltier modules, with at least two Peltier modules in thermal contact with the first tool part and at least two Peltier modules in thermal contact with the second tool part. In this way, multiple thermal zones may be defined on both sides of the chamber, e.g. the mould cavity.

5

The material-handling manufacturing tool, e.g. the moulding tool, may comprise three or more tool parts, e.g. mould parts, where at least one tool part is in thermal contact with at least one Peltier module. The Peltier module may be configured to provide heating and/or cooling.

10

The heat flow measured during cooling of the moulding tool may be divided into three periods in time: an initial cooling period; a solidification period; and a final cooling period.

15 Multiple peaks or troughs in the heat flow or heat capacity of the material-handling manufacturing tool, e.g. the moulding tool, and tool part, e.g. the mould part, may be observed during cooling of the mould. These may correspond to additional transitions such as crystallisation and glass temperatures. The position and size or area of these peaks allows extraction of further information about the properties of the formed part
20 e.g. the part's crystallinity.

The measured heat flow for each thermal zone may be used to create a heat flow profile for at least one, or each, thermal zone. The electronic controller may be configured to use the measured heat flow profile for at least one thermal zone, during
25 the production of a part, to adjust the heat flow profile for use in the at least one thermal zone for the production of the next part. For example, if the crystallinity is too low in one region of the part, the desired temperature cooling rate in the thermal zone(s) for that region may be reduced in the next part production cycle. Therefore, this in-tool analysis, performed during the part production process, may allow much
30 more rapid feedback on part production, enabling rapid optimisation of temperature profiles for the thermal zone(s). This temperature profile optimisation may be automatically calculated from the heat flow analysis.

The analysis of the heat flow and subsequent feedback into the temperature profiles
35 for the thermal zones(s) may be used to compensate, for example, mould wear or

temperature sensor measurement drift or variations in the polymer input materials. Therefore such analysis in-tool may enable a more consistent part production, with improved quality control.

5 Commonly, DSC measurements are performed under controlled temperature ramps, with the heating power required to achieve the target temperatures measured by thermocouples referenced to a reference sample holder with no sample. To perform DSC in the moulding process, estimates of both the heat flow and the temperature is required, where the temperature is rapidly, often non-linearly, changing due to the
10 requirements of the moulding process. Therefore a more sensitive measurement of the heat flow may be required. This for example may be achieved by calculating the heat flow from the ratio between the temperature difference across the Peltier module and its thermal resistance. A Peltier module can give higher voltage signals than temperature sensors such as metallic thermocouples, and therefore more sensitive
15 measurements of the temperature difference, due to the higher Seebeck coefficients of the thermoelectric materials used in a Peltier module as well as it being easy to connect several thermocouples in series in a Peltier module to increase the voltage signal. Therefore, a Peltier module's sensitivity provides an advantage in using it as a measuring device for the heat flow.

20

A second aspect provides a method of manufacture of a part comprising:

providing a manufacturing apparatus according to the first aspect;
using the electronic controller to operate at least one of the Peltier modules;
introducing a liquid and/or semi-liquid material into the chamber; and
25 deriving a measurement indicative of the heat flow through one or more of the Peltier modules.

The manufacturing apparatus may comprise any of the features disclosed in relation to the first aspect.

30

The at least one Peltier module may be connected to a power supply such as a battery or an external power supply such as a mains power supply.

The at least one Peltier module may be powered to act as a heat pump. When operated
35 as a heat pump the at least one Peltier module may transfer heat to a tool part.

The at least one Peltier module may be powered to act as a heat pump before the material is introduced into the chamber and/or as the material is introduced into the chamber.

- 5 The material may comprise a polymer. The polymer may have been heated to a liquid state and/or semi-liquid state. The material may be introduced into the chamber by any suitable means.

10 As the material, such as a polymer, flows and/or packs into the chamber, e.g. the mould cavity, the Peltier module power and/or current direction may be controlled and/or adjusted to provide heating or cooling of one or more tool parts.

The electronic controller may be configured to receive feedback from at least one temperature sensor and to adjust the power and/or current and/or voltage to at least
15 one Peltier module based on the difference between a measured temperature and a desired temperature, for example using thermostatic, pulse width modulation (PWM), and/or a proportional–integral–derivative control.

Feedback from at least one temperature sensor to the electronic controller may be used
20 to control and/or adjust the heating or cooling provided by at least one Peltier module. The electronic controller may control at least one Peltier module such that the temperature of any mould part temperature remains constant or within a prescribed temperature range. The electronic controller may control at least one Peltier module such that the temperature of any tool part, e.g. mould part, increases or decreases to a
25 desired temperature.

In an implementation, in which the material-handling manufacturing tool comprises a moulding tool, once the mould cavity is filled with the material in a liquid or semi-liquid state, the Peltier module(s) may be powered with a current direction opposite to
30 when the Peltier module(s) was acting as a heat pump in order to provide controlled cooling of one or more of the mould parts. In this way, heat may be transferred, for example, to the or a thermal buffer. Feedback from the at least one temperature sensor to the electronic controller may be used to control and/or adjust the rate of cooling or temperature reduction provided by one or more Peltier modules.

For instance, cooling of the mould part(s) mould may allow for more control over the rate of cooling of the material contained within the mould cavity. In this way, the properties of the finished moulded part may be more easily controlled. Once the part has sufficiently cooled, the part may be ejected. The first mould part and at least one
5 further mould part may be separated to allow for ejection of the moulded part. The mould parts may then be reconnected and the moulding of another part may begin.

Advantageously, efficiency gains over known heating and cooling methods may be achieved as the Peltier module(s) is/are transferring heat to and from the or a thermal
10 buffer. In addition, utilising a Peltier module may increase the temperature ramp rates, reducing the time taken to make each part, increasing manufacturing speed.

Each Peltier module present may be operable to provide a measurement of the heat flow through it. Measurement of the heat flow may be derived from a measurement of
15 at least two of the current, voltage or electrical power supplied to the Peltier module. One or more heat flow measurements may be taken at any suitable time. One or more heat flow measurements may be taken as a volume of material enters the mould cavity and/or as the volume of material cools and/or sets inside the mould cavity. The electronic controller may be configured to calculate the heat flow based on
20 measurements from at least one Peltier module.

This heat flow measurement as the temperature changes may provide similar information to a differential scanning calorimetry (DSC) measurement, thus enabling in-tool DSC measurements.
25

The in-tool DSC or heat flow measurement may be performed as the polymer sets or solidifies.

The voltage, V , and current, I , through a Peltier module is related by the expression
30 given in Equation 1 below:

$$V = I * R - \alpha * \Delta T \quad -(1)$$

where R is the electrical resistance of the Peltier module, α is the effective absolute Seebeck coefficient of the module and ΔT is the temperature difference across the Peltier module, i.e. the mould temperature minus the thermal buffer temperature. I is
35 defined such that a positive I results in mould cooling. R and α are weak functions of

temperature so can be assumed constant or corrected for with the known temperature dependent material properties, so that ΔT can be directly calculated with a measurement of V and I of the Peltier module. Since the electrical power to the Peltier module is the product of I and V , then a measurement of the electrical power can be substituted for a measurement of one of I or V . If the temperature difference across the module, ΔT is known, then the heat flow out of the mould, Q , can be calculated by Equation 2:

$$Q = \Delta T / R_{th} + \alpha * I * T_M - 0.5 * I^2 * R \quad -(2)$$

where R_{th} is the thermal resistance of the Peltier module with no current flow and T_M is the mould part temperature.

The electronic controller may be configured to measure any one or more of the voltage and/or the current through the Peltier module and may be configured to also receive data from the temperature sensor(s).

The voltage and current through the Peltier module may be measured to enable a calculation of the heat flow. The heat flow may be analysed directly or converted into a combined heat capacity of the moulding tool and the polymer part by dividing the heat flow by the rate of change of the mould part temperature.

The combined heat capacity of the moulding tool and the polymer part may optionally be divided by the mass of the moulding tool and the polymer part to give the combined specific heat capacity of the moulding tool and the polymer part. The combined heat capacity of the moulding tool and the polymer part may optionally have the known heat capacity of the moulding tool subtracted from it to give the polymer part heat capacity. The polymer part heat capacity may optionally be divided by the mass of the polymer part to give the polymer part specific heat capacity.

The Peltier module may be configured to provide the temperature control by electrically controlled heating and/or cooling of the tool parts where the Peltier module power control depends on feedback from the at least one temperature sensor.

The Peltier module power control may be fixed, for example using a fixed input voltage or fixed duty cycle if PWM control is used and measuring how the current changes or fixing the current input and measuring how the voltage changes.

At least one Peltier module may be electrically driven in a constant state during a heat flow measurement.

5 The power control of at least one Peltier module may be operable to be fixed at one or more pre-determined values. The power control may be fixed at a value to achieve maximum cooling rate. The power control may be fixed at a value to achieve maximum heating rate.

10 The power control of at least one Peltier module may be fixed only around the temperature points where the most sensitive measurements are required, for example around the crystallisation temperature of a semi-crystalline polymer. The pre-determined fixed values of the power control may be variable depending on the material that is to be moulded.

15 At least one Peltier module may be unpowered when taking one or more heat flow measurements. At least one Peltier module may be unpowered when taking the most sensitive heat flow measurements. At least one Peltier module may be unpowered when taking one or more heat flow measurements where a measured or calculated temperature is within a pre-determined range. The pre-determined range may be
20 approximately around the crystallisation temperature of a semi-crystalline polymer that is to be moulded.

When the Peltier module is unpowered, equations 1 and 2 may be simplified to:

$$V_{oc} = -\alpha \Delta T \quad -(3)$$

25 $Q_{oc} = \Delta T / R_{th} . \quad -(4)$

Where V_{oc} is the open circuit voltage, the voltage across the Peltier module with zero current and Q_{oc} is the heat flow through the Peltier module when zero current is applied to the Peltier. A measurement of V_{oc} can therefore be used to measure the heat flow Q_{oc} . This method may also eliminate the requirement to know R and so will
30 increase the sensitivity of the heat flow measurement.

The Peltier module may only be unpowered in order to measure V_{oc} for the duration of time to take the most sensitive measurements. The Peltier module may only be unpowered for one or more short durations, for example to periodically measure V_{oc}
35 and thus sample the temperature difference and heat flow across the Peltier module. In

this way the duration that the Peltier module is turned off, therefore reducing the heat flow, is minimised. By minimising the time the Peltier module is turned off, the cooling time will be minimised. In this way, the short cycle times that are desired for high-speed production may be achieved.

5

The method may comprise using a first Peltier module configured to provide temperature control of the tool parts by electrically controlled heating and/or cooling and may further comprise using a second Peltier module where the second Peltier module is configured to act as a measurement Peltier module for measuring heat flow through the second Peltier module. The second Peltier module may be unpowered.

10

The method may comprise the open circuit voltage of the second Peltier module being monitored to determine the heat flow for the in-tool DSC measurement. The method may comprise the open circuit voltage of the second Peltier module being monitored by the electronic controller. The method may comprise the open circuit voltage of the second Peltier module being monitored by the electronic controller approximately around the crystallisation temperature of a semi-crystalline polymer that is to be handled, e.g. moulded, and/or at pre-determined intervals, and/or as the part to be handled, e.g. moulded, is cooling.

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Measurement of the heat flow may be performed by the measurement of the open circuit voltage of a second independent electrical track on at least one Peltier module.

In this way, an increase in measurement sensitivity from measuring the Peltier module in an unpowered state (i.e. measuring V_{oc}) can be achieved without the undesired reduction in cooling speed.

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The method may comprise using an electronic controller to individually operate a plurality of Peltier modules. The material-handling manufacturing tool, e.g. the moulding tool, may be described as comprising a plurality of thermal zones, where at least one Peltier module is associated with each thermal zone. In this way, the method may comprise using an electronic controller to individually operate a plurality of Peltier modules to individually control the heating and/or cooling of a plurality of thermal zones. The material-handling manufacturing tool may comprise a single thermal zone.

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The material-handling manufacturing tool, e.g. the moulding tool, may comprise an independent temperature sensor for each thermal zone. The method may comprise the electronic controller receiving feedback from each of a plurality of temperature sensors.

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The method may comprise independently thermally controlling each thermal zone by controlling the Peltier module(s) associated with different thermal zones depending on feedback from their corresponding temperature sensor(s).

- 10 Such independent zonal control of temperature allows potential improved temperature uniformity. For example, extra heating may be applied to parts of the moulding tool that have additional cooling losses.

Advantageously, this can allow improved control of viscosity of the filling material,
15 for instance improving filling of the mould. This can allow, for instance, reduced wall thicknesses of parts (lighter components), elimination of weld lines/sink marks, aggressive adjacent section thickness changes. In addition, this can reduce press clamp, fill and closure pressures, because the input material temperature profile is no longer driven by the coldest, thinnest portion of the mould cavity. In addition,
20 controlling cooling rates to be uniform across the moulding tool can reduce thermal stresses and subsequent deformation of parts. As well as allowing increased thermal uniformity, zonal thermal control allows deliberate, advantageous non-uniformities to be generated, for example increasing temperature in some areas of the moulding tool, especially thinner parts, to promote filling of these difficult to fill parts of the
25 moulding tool.

The method may comprise using a multiplexer in the measurement of the temperature sensors. A multiplexer may be used in the measurement of the heat flow through the Peltier modules.

30

The temperature of the tool part(s) may be calculated using the temperature of the thermal buffer and/or the temperature difference across the Peltier module (for example calculated from equation 1 or 3 depending on measurement method).

The method may comprise using measured heat flow for each thermal zone to create a heat flow profile for at least one, or each, thermal zone. The electronic controller may be configured to use the measured heat flow profile for at least one thermal zone, during the production of a part, to adjust the heat flow profile in the at least one thermal zone for the production of the next part. For example if the crystallinity is too low in one region of the part, the desired temperature cooling rate in the thermal zone(s) for that region may be reduced in the next part production cycle. Therefore, this in-tool analysis, performed during the part production process, may allow much more rapid feedback on part production, enabling rapid optimisation of temperature profiles for the thermal zone(s). This temperature profile optimisation may be automatically calculated from the heat flow analysis.

The analysis of the heat flow and subsequent feedback into the temperature profiles for the thermal zones(s) may be used to compensate, for example, mould wear or temperature sensor measurement drift or variations in the polymer input materials. Therefore, such analysis in-tool may enable a more consistent part production, with improved quality control.

Commonly, DSC measurements are performed under controlled temperature ramps, with the heating power required to achieve the target temperatures measured by thermocouples referenced to a reference sample holder with no sample. To perform DSC in the manufacturing, e.g. moulding, process, estimates of both the heat flow and the temperature is required, where the temperature is rapidly, often non-linearly, changing due to the requirements of the moulding process. Therefore a more sensitive measurement of the heat flow may be required. This for example may be achieved by calculating the heat flow from the ratio between the temperature difference across the Peltier module and its thermal resistance. A Peltier module can give higher voltage signals than temperature sensors such as metallic thermocouples, and therefore more sensitive measurements of the temperature difference, due to the higher Seebeck coefficients of the thermoelectric materials used in a Peltier module as well as it being easy to connect several thermocouples in series in a Peltier module to increase the voltage signal. Therefore, a Peltier module's sensitivity provides an advantage in using it as a measuring device for the heat flow.

The skilled person will appreciate that except where mutually exclusive, a feature or parameter described in relation to any one of the above aspects may be applied to any other aspect. Furthermore, except where mutually exclusive, any feature or parameter described herein may be applied to any aspect and/or combined with any other feature or parameter described herein.

Example embodiments will now be described with reference to the accompanying drawings, in which:

- Figure 1 is a schematic of an example of a manufacturing apparatus comprising a moulding tool and a Peltier module;
Figure 2 is a schematic of the electrical interconnects for a dual track Peltier module;.
Figure 3 is a schematic of an example of a manufacturing apparatus comprising a moulding tool and a plurality of Peltier modules;
Figure 4 is a schematic of an example of a manufacturing apparatus comprising a moulding tool with multiple Peltier modules on both sides;
Figure 5 is an example of the heat flow measured during cooling of a polymer part; and
Figure 6 illustrates an example method of manufacture.

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Figure 1 shows a manufacturing apparatus 1 comprising a two-part moulding tool 100. A first mould part 101 and a second mould part 102 together define a mould cavity 110. The mould cavity 110 shape defines the shape of a part to be made. In some embodiments, a polymer is injected into the mould cavity 110 to form the desired polymer part. A first Peltier module 103 is in thermal contact with the first mould part 101 and a first thermal buffer 104. The temperature of the first mould part 101 is detected by a temperature sensor 120. The first mould part 101 and the second mould part 102 are connectable to and disconnectable from each other. When the first mould part 101 and the second mould part 102 are connected to each other, the mould cavity 110 is a substantially sealed space. The temperature sensor 120 is disposed within a body of the first mould part 101.

The first mould part 101 and the second mould part 102 may comprise any suitable dimensions. The mould cavity 110 may comprise any suitable shape and dimensions such that it corresponds to the shape of the desired part to be moulded.

The first Peltier module 103 comprises a substantially planar shape having two opposing faces. A first face is arranged parallel to and in thermal contact with at least a portion of an external surface of the first mould part 101. The first face of the first Peltier module 103 is arranged to extend across at least a portion of an external surface of the first mould part 101.

A second face of the first Peltier module 103 is arranged parallel to and in thermal contact with at least a portion of an external surface of the first thermal buffer 104. The second face of the first Peltier module 103 is arranged to extend across at least a portion of an external surface of the first thermal buffer 104.

When moulding a polymer part, in a first stage the first Peltier module 103 is powered to act as a heat pump, pumping heat from the first thermal buffer 104 to the first mould part 101, thereby heating up both the first mould part 101 and the second mould part 102 to the desired temperature using feedback from the temperature sensor 120. This feedback may utilise electronic control to adjust the power and/or current and/or voltage to the Peltier module 120 based on the difference between the measured temperature and the desired temperature, for example using thermostatic, pulse width modulation (PWM), and/or a proportional–integral–derivative control. An electronic controller 105 is operably connected to the temperature sensor 120 and the first Peltier module 103 and is operable to electronically control the first Peltier module 103 based on the feedback from the temperature sensor 120.

In a second stage, a volume of polymer in a liquid and/or semi-liquid form is injected into the mould cavity 110. As the polymer flows and/or packs into the mould cavity 110, the Peltier module 103 power and current direction is controlled by the electronic controller 105 to provide heating or cooling, using feedback from the temperature sensor 120. The electronic controller 105 controls the Peltier module 103 to keep the mould temperature constant or within a prescribed temperature range.

Once the mould cavity 110 is correctly filled, a third stage starts. In the third stage, the Peltier module 103 is powered with a current direction opposite to the first stage, to provide controlled cooling of the first and second mould parts 101, 102, pumping heat into the thermal buffer 104. Once the first and second mould parts 101, 102 and the moulded polymer part have sufficiently cooled, the polymer part can be ejected

and the cycle repeated. Efficiency gains over other heating and cooling methods can be achieved, as the first Peltier module 103 is pumping heat to and from the thermal buffer 104. In addition, utilising a Peltier module, e.g. the first Peltier module 103, can increase the temperature ramp rates, reducing the time taken to make each part, increasing manufacturing speed.

An in-tool DSC or heat flow measurement may be performed during the third stage, as the polymer part sets or solidifies. In other embodiments, the in-tool DSC or heat flow measurement may be performed during the first, second and/or third stage.

10

The voltage, V , and current, I , through a Peltier module is related by the expression given in Equation 1 below:

$$V = I * R - \alpha * \Delta T \quad -(1)$$

where R is the electrical resistance of the Peltier module, α is the effective absolute Seebeck coefficient of the Peltier module and ΔT is the temperature difference across the Peltier module, i.e. the mould temperature minus the thermal buffer temperature. I is defined such that a positive I results in mould cooling. R and α are weak functions of temperature so can be assumed constant or corrected for with the known temperature dependent material properties, so that ΔT can be directly calculated with a measurement of V and I of the Peltier module. Since the electrical power to the Peltier module is the product of I and V , then a measurement of the electrical power can be substituted for a measurement of one of I or V . If the temperature difference across the module, ΔT is known, then the heat flow out of the mould, Q , can be calculated by Equation 2:

$$25 \quad Q = \Delta T / R_{th} + \alpha * I * T_M - 0.5 * I^2 * R \quad -(2)$$

where R_{th} is the thermal resistance of the Peltier module with no current flow and T_M is the mould temperature. Therefore, in one embodiment the voltage and current through the Peltier module may be measured to enable a calculation of the heat flow. The heat flow can be analysed directly or converted into a combined heat capacity of the moulding tool and polymer part by dividing the heat flow by the rate of change of the mould temperature. The combined heat capacity of the moulding tool and the polymer part can be optionally divided by the mass of the moulding tool and the polymer part to give the combined specific heat capacity of the moulding tool and the polymer part. The combined heat capacity of the moulding tool and the polymer part may optionally have the known heat capacity of the moulding tool subtracted from it

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to give the polymer part heat capacity. The polymer part heat capacity may be optionally divided by the mass of the polymer part to give the polymer part specific heat capacity.

- 5 Using the voltage and current of the first Peltier module 103 to calculate the heat flow may be more challenging when tight control of the cooling rate is needed, as the voltage and/or current and/or power supplied to the first Peltier module 103 may be rapidly changing, complicating sensitive measurements of the current and voltage or requiring more complex and expensive monitoring methods. In one embodiment, the
10 first Peltier module 103 power control may be fixed, for example using a fixed input voltage or fixed duty cycle if pulse width modulation (PWM) control is used and measuring how the current changes or fixing the current input and measuring how the voltage changes. The power control may be fixed at a value to achieve a maximum cooling rate. The power control may be fixed only around the temperature points
15 where the most sensitive measurements are required, for example around the crystallisation temperature of a semi-crystalline polymer.

In some embodiments, the first Peltier module 103 may be unpowered when taking the most sensitive heat flow measurements. This significantly simplifies equation 1 and 2
20 to:

$$V_{oc} = -\alpha \Delta T \quad -(3)$$

$$Q_{oc} = \Delta T / R_{th} . \quad -(4)$$

Where V_{oc} is the open circuit voltage, the voltage across the Peltier module with zero current and Q_{oc} is the heat flow through the Peltier module when zero current is
25 applied to the Peltier module. A measurement of V_{oc} can therefore be used to measure the heat flow Q_{oc} . This method also eliminates the requirement to know R and so will increase the sensitivity of the heat flow measurement. However, unfortunately, by turning off the current to the Peltier module, reducing the heat flow, the cooling time will be increased, which conflicts with the short cycle times that are desired for high-
30 speed production. The first Peltier module 103 may only be unpowered in order to measure an open circuit voltage V_{oc} for the duration of time to take the most sensitive measurements. The first Peltier module 103 may only be unpowered for multiple short durations, for example to periodically measure the open circuit voltage V_{oc} and thus sample the temperature difference and heat flow across the first Peltier module 103.

Another embodiment seeks to balance the increase in measurement sensitivity from measuring the Peltier module in an unpowered state (i.e. measuring V_{oc}) with the undesired reduction in cooling speed. In some such embodiments, a second Peltier module can be used, where the first Peltier module 103 provides the temperature control by electrically controlled heating and cooling operated by the electronic controller, and is therefore electrically powered at a level that depends on feedback from the temperature sensor 120, while the second Peltier module acts as a measurement Peltier module, so is unpowered, with its open circuit voltage monitored to determine the heat flow for an in-tool DSC measurement. The second Peltier module may act continuously or intermittently as a measurement Peltier module, i.e. the second Peltier module may be permanently unpowered or intermittently unpowered for the time(s) when a measurement is to be made.

The second Peltier module may be smaller than the first Peltier module 103 to reduce the loss in cooling and heating control while still maintaining the more sensitive monitoring of an unpowered Peltier module. For instance, the second Peltier module may have at least five times fewer thermoelectric elements than the first Peltier module 103, to reduce the impact on cooling and heating control. For example, the second Peltier module may have at least five times less thermoelectric material area perpendicular to the heat flow than the first Peltier module 103.

To simplify assembly, and reduce any temperature gradients in the mould due to differences in heat flow in the first and second Peltier modules, the first and second Peltier modules may be integrated so that the first and second Peltier modules may share the same substrates but be electrically isolated from each other, i.e. the first and second Peltier modules may be integrated together into one single Peltier module with dual tracks, two separate continuous electrical series circuits controlling different areas of thermoelectric elements within the Peltier module.

An example of an interconnect pattern for such a dual track Peltier module 203, is shown in plan view in Figure 2, where the first interconnects 230 on a first substrate and the second interconnects 231 on a second substrate are shown. The substrates and the thermoelectric elements that together with the interconnects 230, 231 make up the Peltier module are not shown for clarity. Typically, the n- and p-type thermoelectric elements would be disposed in a chequerboard fashion between the first and second

interconnects 230, 231 in areas where the first and second interconnects 230, 231 overlap. A first continuous series circuit for the heating and cooling control can be accessed by using the external connections 241, 242, while a second continuous series circuit for the measurement of the heat flow through its open circuit voltage can be accessed through the external connections 243, 244. These two electrical circuits are electrically isolated from one another by the insulating substrate. For example, the second continuous series circuit may have at least five times fewer thermoelectric elements than the first continuous series circuit. For instance, the second continuous series circuit may have at least five times less thermoelectric material area perpendicular to the heat flow than the first continuous series circuit.

Figure 3 shows a manufacturing apparatus 3 comprising a moulding tool 300 and five Peltier modules 303a 303b, 303c, 303d, 303e. The moulding tool 300, which may be a two-part polymer moulding tool, comprises a first mould part 301 and a second mould part 302, which together define a mould cavity 310. The mould cavity 310 shape defines the shape of a part, e.g. a polymer part, to be made. In the example shown in Figure 3, the mould cavity 310 has a shape for forming a part with a thicker section 311 and a thinner section 312. The five Peltier modules 303a, 303b, 303c, 303d, 303e are each in thermal contact with the first mould part 301 and a thermal buffer 304. Five temperature sensors 320a, 320b, 320c, 320d, 320e are arranged to measure the temperature of the first mould part 301 at five different locations, each temperature sensor 320a, 320b, 320c, 320d, 320e being located close to one of the Peltier modules 303a, 303b, 303c, 303d, 303e. The moulding tool 300 may be considered to include five thermal zones with each zone being associated with one Peltier module 303a, 303b, 303c, 303d, 303e and one temperature sensor 320a, 320b, 320c, 320d, 320e. An example of a thermal zone 350 is indicated in Figure 3. An electronic controller 305 is operably connected to the five Peltier modules 303a, 303b, 303c, 303d, 303e and the five temperature sensors 320a, 320b, 320c, 320d, 320e.

By utilising multiple temperature sensors, e.g. the five temperature sensors 320a, 320b, 320c, 320d, 320e, and multiple Peltier modules, e.g. the five Peltier modules 303a, 303b, 303c, 303d, 303e, different thermal zones of the moulding tool can be defined, with, for example, one temperature sensor and one Peltier module per thermal zone. Each thermal zone can therefore be independently thermally controlled, with Peltier modules associated with different thermal zones electrically driven in different

ways by an electronic controller depending on their corresponding temperature sensor reading and the desired temperature for that thermal zone.

Such independent zonal control of temperature allows potential improved temperature
5 uniformity, for example to apply extra heating to parts of the moulding tool that have
additional cooling losses. This can allow improved control of viscosity of the filling
material, improving filling of the mould cavity. This can allow reduced wall
thicknesses of parts (lighter components), elimination of weld lines/sink marks,
aggressive adjacent section thickness changes. In addition, this can reduce press
10 clamp, fill and closure pressures, because the input material temperature profile is no
longer driven by the coldest, thinnest portion of the mould cavity. In addition,
controlling cooling rates to be uniform across the moulding tool can reduce thermal
stresses and subsequent deformation of parts. As well as allowing increased thermal
uniformity, zonal thermal control allows deliberate, advantageous non-uniformities to
15 be generated, for example increasing temperature in some areas of the moulding tool,
especially thinner parts, to promote filling of these difficult to fill parts of the mould
cavity.

In some embodiments, each independently controlled thermal zone may have more
20 than one Peltier module.

In some embodiments, each independently controlled thermal zone may have more
than one temperature sensor.

25 To increase heating and cooling ramp rates, the thermal buffer may also be actively
heated or cooled during the thermal cycle. For example, the thermal buffer may be
additionally heated during or immediately prior to a first heating stage or a second
hold stage.

30 For instance, to increase heating ramp rates, additional heating, e.g. additional
electrical heating, may be applied to one or more of the mould parts.

In some embodiments, the thermal buffer may comprise a heat exchanger. The thermal
buffer may comprise a heat sink. The thermal buffer may comprise a heat sink with a
35 fan or a blower. The fan or blower speed may be altered during different parts of the

thermal cycle, for example at maximum speed during or immediately prior to the period of maximum cooling. The thermal buffer may be split into multiple parts to aid assembly.

- 5 A multiplexer may be used in the measurement of the temperature of the mould part(s) by the temperature sensor(s). A multiplexer may be used in the measurement of the heat flow through the Peltier module(s).

10 In some embodiments, one or more of the temperature sensors may be disposed at least partially in the thermal buffer, where there may be more space for installation. The temperature of the mould part(s) may be calculated using the temperature of the thermal buffer and the temperature difference across the one or more Peltier modules (for example calculated from equation 1 or 3 depending on measurement method).

- 15 Figure 4 shows another example of a manufacturing apparatus 4 comprising a moulding tool 400. The moulding tool 400 comprises a first mould part 401 and a second mould part 402, which together define a mould cavity 410. The mould cavity 410 shape defines the shape of a part, e.g. a polymer part, to be made.

- 20 A first Peltier module 403 is in thermal contact with the first mould part 401 and a first thermal buffer 404. A first temperature sensor 420 is arranged to measure the temperature of the first mould part 401.

- 25 A second Peltier module 413 is in thermal contact with the second mould part 402 and a second thermal buffer 414. A second temperature sensor 421 is arranged to measure the temperature of the second mould part 402.

- 30 A controller 405, e.g. an electronic controller, is operably connected to the first Peltier module 403, the second Peltier module 413, the first temperature sensor 420 and the second temperature sensor 421. In use, the first temperature sensor 420 and the second temperature sensor 421 provide feedback to the controller. The controller may modify operation of the first Peltier module 403 in response to feedback from the first temperature sensor 420, in order to achieve a desired temperature. The controller may modify operation of the second Peltier module 413 in response to feedback from the
35 second temperature sensor 421, in order to achieve a desired temperature.

The moulding tool 400 may be considered to have a first thermal zone and a second thermal zone. The first Peltier module 403 and the first temperature sensor 420 are associated with the first thermal zone. The second Peltier module 413 and the second temperature sensor 421 are associated with the second thermal zone.

In some embodiments, there may be at least four Peltier modules, with at least two Peltier modules in thermal contact with the first mould part and at least two Peltier modules in thermal contact with the second mould part. In this way, multiple temperature control zones can be defined from both sides of the mould.

In some embodiments, the moulding tool may comprise three or more mould parts, with at least one mould part in thermal contact with at least one Peltier module to provide both the heating and/or cooling, and/or to provide a measurement of the heat flow therethrough. In some embodiments, the moulding tool may have at least four, at least five or at least six mould parts.

The heat flow measured during cooling of a moulding tool may have the form shown in Figure 5 for a polymer part. The cooling can be divided into three periods in time: an initial cooling period 501; a solidification period 502; and a final cooling period 503. In the initial cooling period 501, the cooling rate is faster than in the final cooling period 503 as the temperature difference between the mould part(s) and the thermal buffer and/or the mould part(s) and ambient temperature is higher. During the solidification period 502, if no solidification occurs, the heat flow would continue to follow the dashed line 511, smoothly dropping between the initial cooling period 501 and the final cooling period 503. If solidification of the polymer occurs, additional heat is generated in the part, so the heat flow is higher, following the solid line 510 (assuming that the same desired temperature cooling profile is achieved). The area between the solid line 510 and the dashed line 511 is the heat of melting or heat of fusion of the part. This area can, for example, be calculated if the dashed line is known by extrapolating a fitting function to the initial cooling period 501 and/or the final cooling period 503. This fitting function may be an exponential function. Calculation of the additional heat generated in the part from solidification may also be performed by examination of the peaks in a plot of heat flow divided by the rate of

change of mould temperature (the combined heat capacity of the mould and part) plotted against time or mould temperature.

Multiple peaks or troughs in the heat flow or heat capacity of the mould and part may be observed. These may correspond to additional transitions such as crystallisation and glass temperatures. The position and size or area of these peaks allows extraction of further information about the properties of the formed part e.g. the part's crystallinity.

The measured heat flow profile for each thermal zone may be used to adjust the desired temperature profile in each thermal zone for the production of the next part. For example, if the crystallinity is too low in one region of the part, the desired temperature cooling rate in the thermal zone(s) for that region can be reduced in the next part production cycle. Therefore this in-tool analysis, performed during the part production process, can allow much more rapid feedback on part production, enabling rapid optimisation of temperature profiles for the thermal zone(s). This temperature profile optimisation may be automatically calculated from the heat flow analysis.

The analysis of the heat flow and subsequent feedback into the temperature profiles for the thermal zones(s) can be used to compensate, for example, for mould wear or temperature sensor measurement drift or variations in the input material(s), e.g. polymer input material(s). Therefore, such analysis in-tool enables a more consistent part production, with improved quality control.

Figure 6 illustrates schematically a method of manufacture 600 according to the present disclosure.

The method of manufacture 600 may be carried out using a manufacturing apparatus described herein. The method of manufacture 600 may be performed to mould a polymer part.

In a first step 601, one or more Peltier modules arranged in thermal contact with one or more mould parts of the moulding tool is/are powered to act as a heat pump, whereby each Peltier module pumps heat to a mould part to a desired temperature using feedback from a temperature sensor.

In a second step 602, a volume of polymer in a liquid and/or semi-liquid form is injected into the mould cavity. As the polymer flows and/or packs into the mould cavity, the Peltier module(s)' power and current direction is controlled by an electronic controller to provide heating or cooling, using feedback from the temperature sensor(s). The electronic controller may control the Peltier module(s) to keep the mould temperature constant or within a prescribed temperature range.

Once the mould cavity is correctly filled, a third stage 603 starts. In the third stage 603, the Peltier module(s) is/are powered with a current direction opposite to the first stage, to provide controlled cooling of the mould part(s). Once the mould part(s) and the moulded polymer part have sufficiently cooled, the polymer part can be ejected and the cycle repeated.

The or a controller operably connected to the Peltier module(s) is arranged to derive a measurement indicative of the heat flow through one or more of the Peltier modules. Hence, at least one in-tool DSC or heat flow measurement 604 may be performed during the third step 603, as the polymer part sets or solidifies. In other embodiments, the in-tool DSC or heat flow measurement may be performed during the first step 601, the second step 602 and/or the third step 603.

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The moulding tools described herein may be suitable for injection moulding, compression moulding, blow moulding, vacuum forming or any other suitable thermoforming moulding process.

While the examples described herein have referred to moulding tools, it will be appreciated that the teaching of the present disclosure may be applied to other types of material-handling manufacturing tools, e.g. dies such as injection dies or extrusion dies.

In general, the teaching of the present disclosure may be applied to any material-handling manufacturing tool for forming a part by a process involving heating and/or cooling one or more materials.

It will be understood that the invention is not limited to the embodiments above-described and various modifications and improvements can be made without departing

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from the concepts described herein. Except where mutually exclusive, any of the features may be employed separately or in combination with any other features and the disclosure extends to and includes all combinations and sub-combinations of one or more features described herein.

CLAIMS

1. A manufacturing apparatus comprising:
a material-handling manufacturing tool comprising a first tool part defining at
5 least partially a chamber for holding or conveying a material during a manufacturing
process;
at least one Peltier module in thermal contact with the first tool part that is
configured to provide temperature control of the tool part by electrically controlled
heating and/or cooling; and
10 an electronic controller configured to operate each Peltier module present;
wherein the electronic controller is arranged to derive a measurement indicative of the
heat flow through one or more of the Peltier modules.
2. A manufacturing apparatus according to claim 1 comprising one or more
15 further tool parts.
3. A manufacturing apparatus according to claim 2, wherein at least one Peltier
module is in thermal contact with each further tool part.
- 20 4. A manufacturing apparatus according to any one of the preceding claims,
wherein one or more of the Peltier modules is/are in thermal contact with a thermal
buffer.
5. A manufacturing apparatus according to any one of the preceding claims,
25 wherein the material-handling manufacturing tool comprises a moulding tool.
6. A manufacturing apparatus according to any one of the preceding claims
comprising a plurality of Peltier modules in thermal contact with the first tool part.
- 30 7. A manufacturing apparatus according to claim 6, wherein each Peltier module
in thermal contact with the first tool part is in thermal contact with the same thermal
buffer, or two or more individual thermal buffers.

8. A manufacturing apparatus according to claim 2, or any one of claims 3 to 7 when dependent on claim 2, comprising a plurality of Peltier modules in thermal contact with the second tool part.
- 5 9. A manufacturing apparatus according to claim 8, wherein each Peltier module in thermal contact with the second tool part is in thermal contact with the same thermal buffer, or two or more individual thermal buffers.
- 10 10. A manufacturing apparatus according to any one of the preceding claims comprising at least one temperature sensor.
11. A manufacturing apparatus according to claim 10, wherein at least one temperature sensor is disposed near, on or at least partially within the first tool part.
- 15 12. A manufacturing apparatus according to any one of the preceding claims, wherein the measurement indicative of the heat flow through one or more of the Peltier module is derived from a measurement of at least two of the current, voltage or electrical power supplied to the Peltier module.
- 20 13. A manufacturing apparatus according any one of the preceding claims, wherein the electronic controller is programmable with one or more pre-determined desired temperatures.
- 25 14. A manufacturing apparatus according to any one of claims 1 to 13 comprising a first Peltier module that is configured to provide temperature control of the tool part(s) by electrically controlled heating and/or cooling and a second Peltier module, wherein the second Peltier module is configured to act as a measurement Peltier module for measuring heat flow through the second Peltier module.
- 30 15. A manufacturing apparatus according to claim 14, wherein the second Peltier module is unpowered. The open circuit voltage of the second Peltier module may be monitored to determine the heat flow for the in-tool DSC measurement.
- 35 16. A manufacturing apparatus according to claim 14 or claim 15, wherein the second Peltier module is smaller than the first Peltier module.

17. The first and second Peltier modules may be integrated so that the first and second Peltier module share the same substrate but are electrically isolated from each other.

5

18. A manufacturing apparatus according to any one of the preceding claims, wherein the material-handling manufacturing tool comprises a plurality of thermal zones, wherein each thermal zone is associated with at least one Peltier module.

10 19. A manufacturing apparatus according to claim 18 comprising at least one temperature sensor for each thermal zone.

20. A manufacturing apparatus according to any one of the preceding claims comprising at least four Peltier modules, with at least two Peltier modules in thermal contact with the first tool part and at least two Peltier modules in thermal contact with the or a second tool part.

21. A method of manufacture of a part comprising:
providing a manufacturing apparatus according to the first aspect;
20 using the electronic controller to operate at least one of the Peltier modules;
introducing a liquid and/or semi-liquid material into the chamber; and
deriving a measurement indicative of the heat flow through one or more of the Peltier modules.

25 22. A method of manufacture of a part according to claim 21, wherein the material-handling manufacturing tool comprises a moulding tool and the method is performed to mould a polymer part.

30

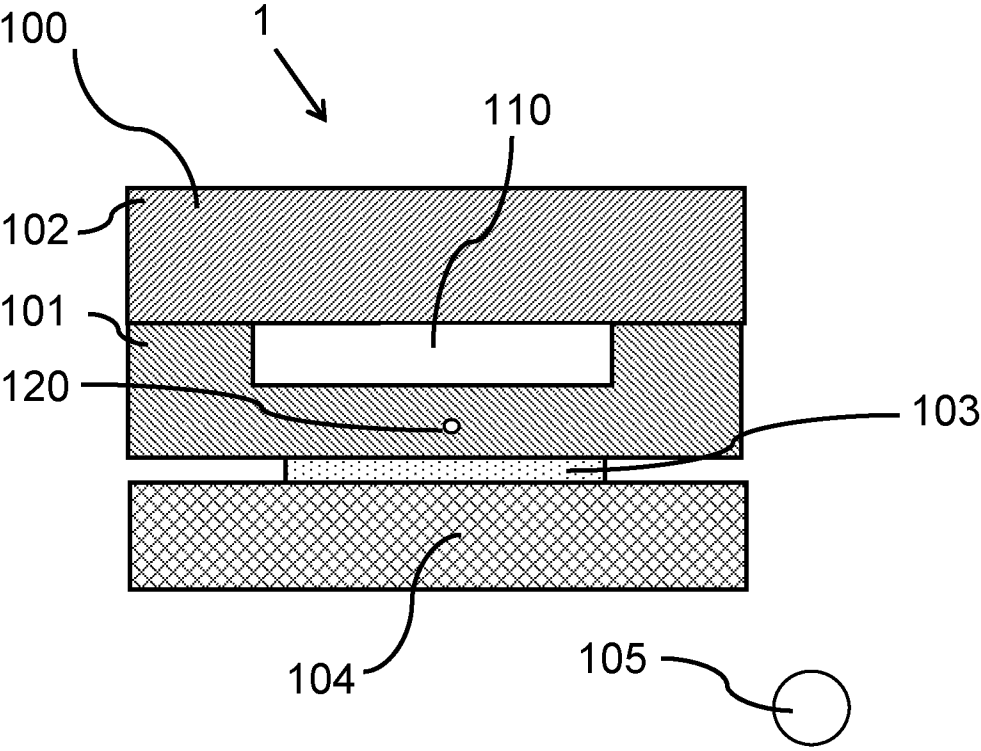


Figure 1

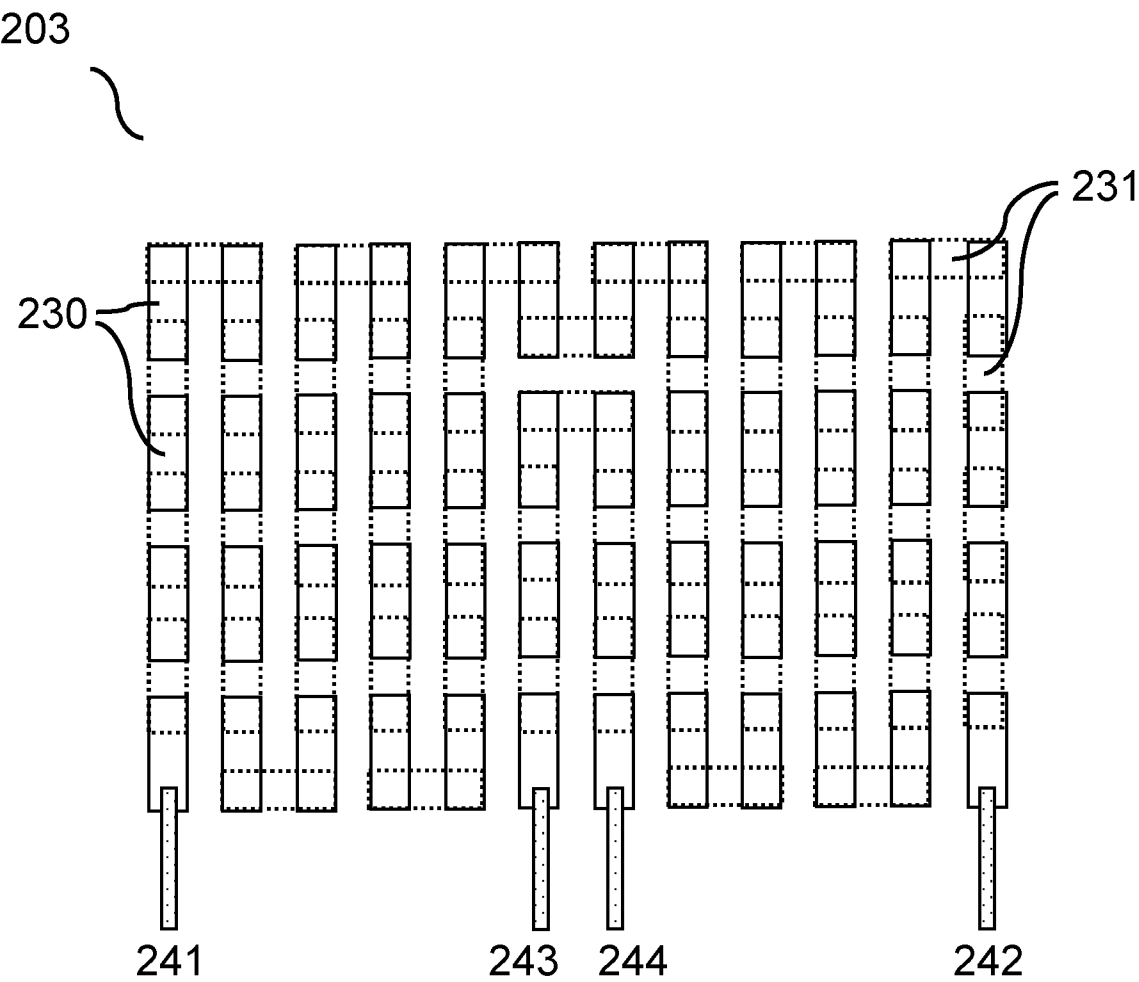


Figure 2

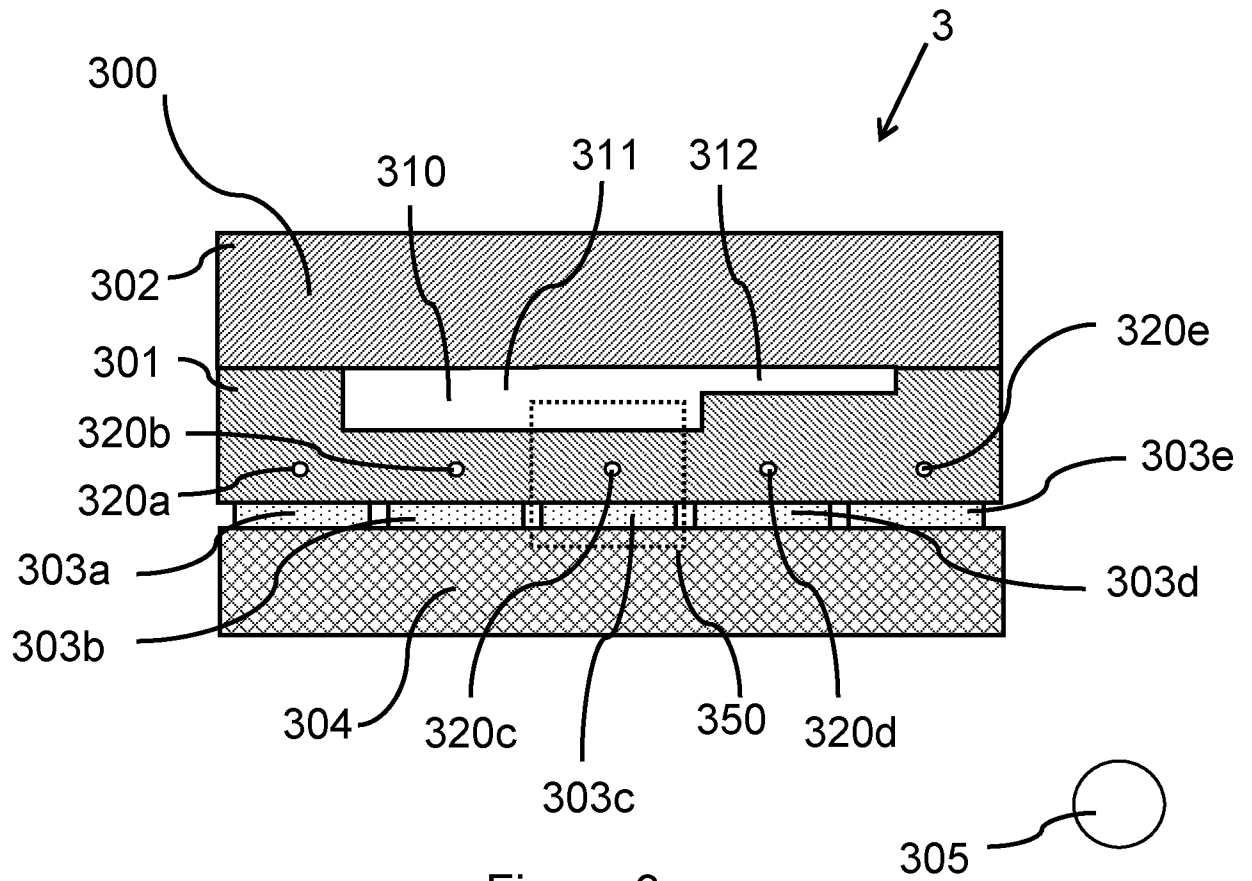


Figure 3

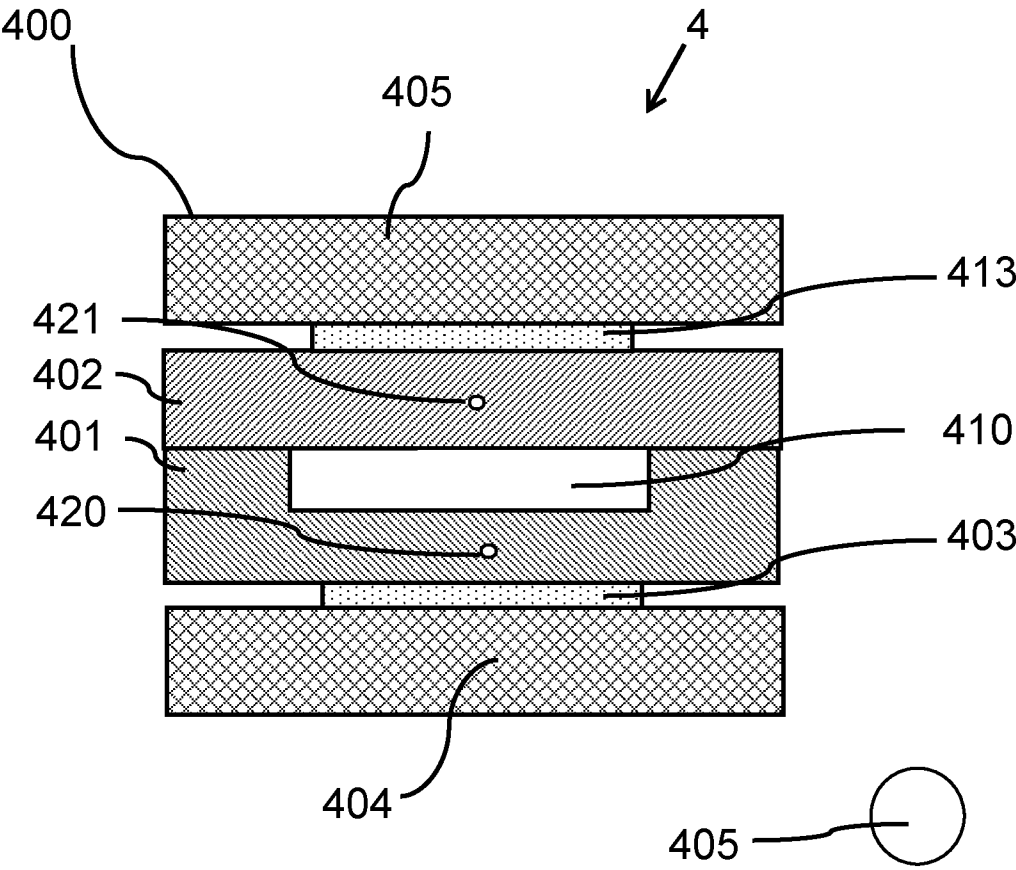


Figure 4

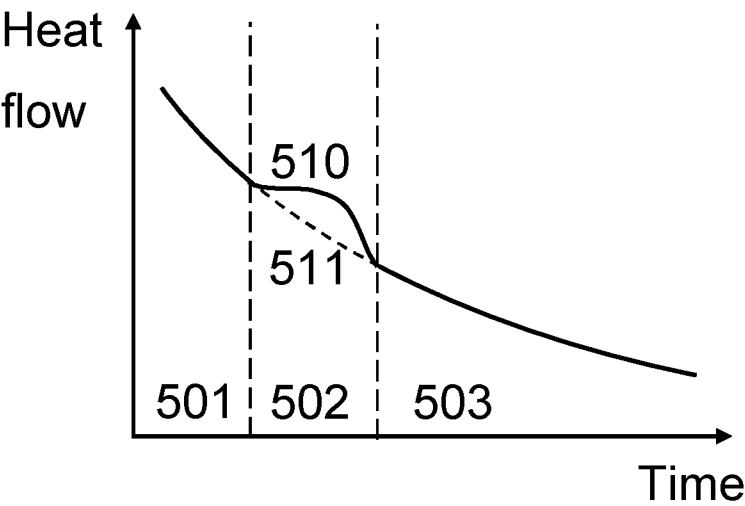


Figure 5

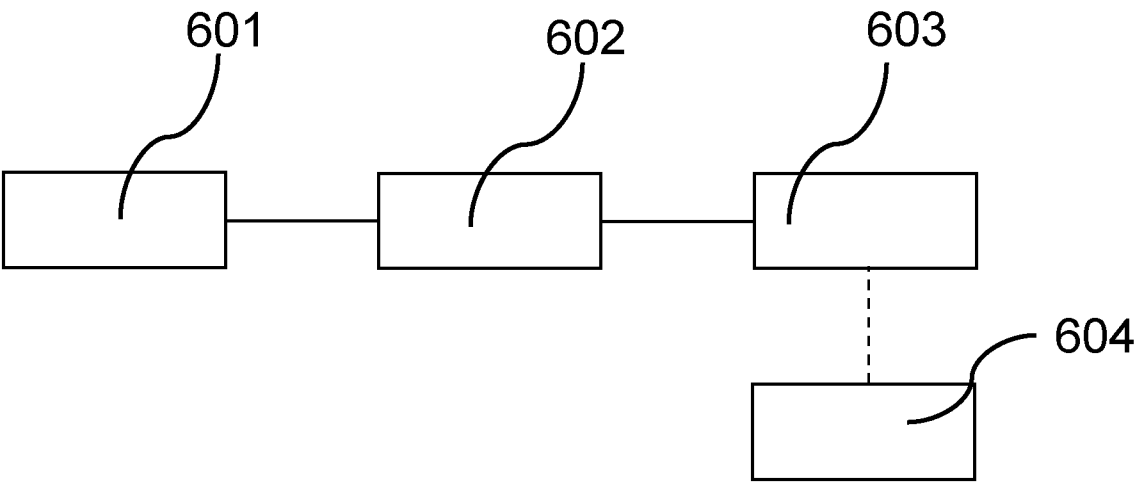


Figure 6

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2022/051962

A. CLASSIFICATION OF SUBJECT MATTER

INV. B29C33/02 B29C45/73

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)

B29C

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	JP H10 52842 A (NEC CORP) 24 February 1998 (1998-02-24)	1-7, 10-18, 20-22
Y	paragraphs [0016] - [0029]; figures 2-7 -----	8, 9, 19
X	JP S57 89929 A (DAINIPPON PRINTING CO LTD) 4 June 1982 (1982-06-04)	1, 2, 4-7, 10-14, 21
Y	paragraph [0002]; figures 1-5 -----	8, 9, 19
X	WO 2007/121934 A1 (TECOS SLOVENIAN TOOL AND DIE D [SI]; ZAGAR BOSTJAN [SI] ET AL.) 1 November 2007 (2007-11-01) cited in the application page 9, line 11 - page 12, line 18; figures 1-8 -----	1, 2, 4-6, 10-13, 21, 22



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

11 October 2022

Date of mailing of the international search report

19/10/2022

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2022/051962

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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JP S5789929	A	04-06-1982	JP H0137252 B2 04-08-1989
		JP S5789929 A	04-06-1982
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