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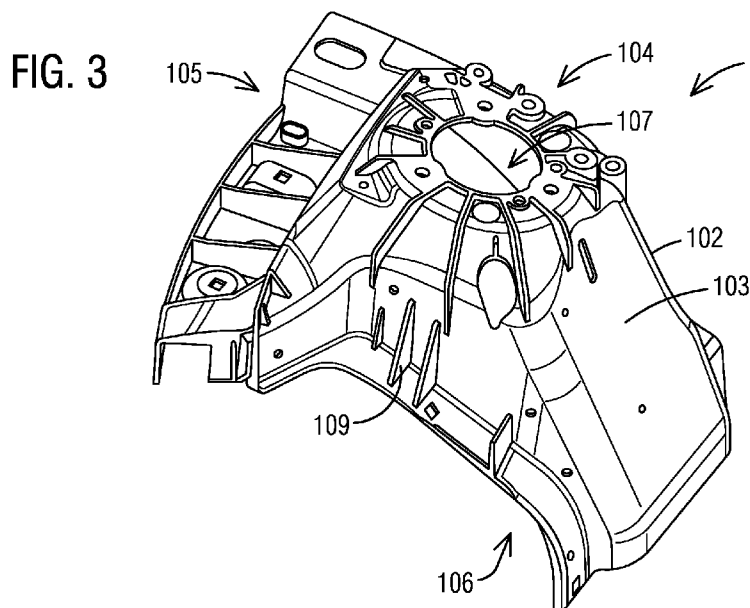
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(54) Title: METHODS FOR IMPROVING THE THERMAL TREATMENT OF CASTINGS



(57) Abstract: A method for improving the thermal treatment of castings that includes obtaining a plurality of untreated castings of a given design, capturing three dimensional surface measurements of the untreated castings to determine a baseline shape, obtaining a first support fixture having a first support profile configured to support the castings during thermal treatment, and then applying a thermal treatment protocol to a first casting while supported on the first support fixture. The method further includes capturing a three dimensional surface measurement of the first casting to determine its post-treatment shape, comparing the baseline shape with the post-treatment shape of the first casting, and identifying a dimensional distortion that is the result of inadequate support or positioning during the thermal treatment protocol. The method continues with obtaining a second support fixture with a second support profile different from the first support profile, applying the thermal treatment protocol to a second casting while supported on the second support fixture, capturing a three dimensional surface measurement of the second casting to

determine its post-treatment shape, comparing the baseline shape with the post-treatment shape of the second casting, and then identifying a reduction in the dimensional distortion to verify that the dimensional distortion is at least partially due to inadequate support or positioning during the thermal treatment protocol.



METHODS FOR IMPROVING THE THERMAL TREATMENT OF CASTINGS

FIELD

[0001] The present invention relates generally to methods for improving the thermal treatment of castings during thermal treatment cycles such as solution heat treatment, quenching and aging, and in particular to a method for improving the thermal treatment of castings formed in an HPDC process.

BACKGROUND

[0002] Historically, the thermal treatment of thin wall aluminum alloy castings that have been formed in a high pressure die cast (HPDC) process, so as to improve their metallurgical properties and performance in high-demand applications, is problematic and often results in defective parts and high scrap rates. For example, these types of castings often have complex shapes, surface features, apertures, and variations in their cross-sectional thickness that make it difficult to apply thermal treatments to the castings in a uniform manner during a typical high-volume production process. It has been found that unevenly-applied thermal treatments can often create large temperature gradients through the thickness or across the expanse of the alloy material during thermal treatment, resulting in dimensional distortions that remain set within the casting material after the thermal treatments are completed and the casting has returned to an ambient equilibrium temperature. In addition, the casting can also be particularly prone to distortion if not properly supported during thermal treatments, such as a solution heat treatment cycle, that raise its temperature to elevated levels that soften the alloy material and allow the thin wall portions to sag under their own weight or to deflect or buckle under the weight of heavier overlying portions. Whether caused by temperature gradients or by sagging or buckling, if the dimensional distortion of the casting after thermal treatment exceeds predetermined tolerances, the casting is generally scrapped.

[0003] Previous attempts to control the sagging, deflection or buckling created during solution heat treatments through improved casting support systems include full position fixtures, not shown but known to one of skill in the art, that are tightly or with close tolerances clamped around the castings shortly after their removal from the die, and which then travel with the castings throughout the thermal treatments to rigidly support and constrain the castings so as to reduce sagging and other distortions that could pull the metallic parts out of dimensional tolerance. However, full position fixtures become more difficult to create with increased complexity and variation in the castings, and by their very presence can often impede or block the flow of thermal fluids to portions of the casting material, thereby exacerbating the temperature gradients within the part. This can lead to the formation of internal stresses that cause the castings to spring out of shape when the full position fixtures are removed after the thermal treatments are complete.

[0004] In addition, previous attempts to control the application of thermal fluids (e.g. heated air, cooling air, water, oil, glycol, and the like) to the castings during the thermal treatments that apply large and/or rapid temperature changes to the part (e.g. solution heat treatment and quenching), so as to reduce or avoid the creation of large temperature gradients within and across the part, have also meet with limited success.

SUMMARY

[0005] Briefly described, one embodiment of the present disclosure comprises a method for improving the thermal treatment of castings, as especially high volume production castings, for enhanced metallurgical properties. The method includes the steps of obtaining a plurality of untreated castings of a given casting design, followed by capturing three dimensional surface measurements of the untreated castings to determine a baseline three dimensional shape for the castings. The method also includes obtaining a first support fixture having a first support profile that is configured to support the castings within one or more thermal treatment zones, and then applying a thermal treatment protocol to a first casting that is supported on the first support fixture within the one or more thermal treatment zones. The method further includes capturing a three dimensional surface measurement of the first casting to determine its post-treatment three dimensional shape, comparing the baseline shape with the post-treatment shape of the first casting, and then identifying one or more correctable dimensional distortions in the first casting that are the result of inadequate support or positioning during the thermal treatment protocol. The method then continues with the steps of obtaining a second support fixture that is configured to support the castings with a second support profile that is different from the first support profile, applying the thermal treatment protocol to a second casting that is supported on the second support fixture. The method further includes the steps of capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape, comparing the baseline shape with the post-treatment shape of the second casting, and then identifying a reduction in a dimensional distortion to verify that the dimensional distortion is at least partially due to inadequate support or positioning during the thermal treatment protocol.

[0006] Another embodiment of the disclosure comprises a method for improving the thermal treatment of castings for enhanced metallurgical properties that includes the steps of obtaining a plurality of untreated castings of a given casting design, followed by capturing three dimensional surface measurements of the castings to determine a baseline three dimensional shape for the castings. The method also includes obtaining a support fixture having an open lattice construction with a plurality of top edges that together define an open support surface that is substantially complementary with an underside surface of the castings, and that is configured to loosely support the castings atop the lattice and orientate the castings in space above the support fixture. The method further includes

applying a thermal treatment protocol to a first casting supported on the support fixture, capturing a three dimensional surface measurement of the first casting to determine its post-treatment three dimensional shape, comparing the baseline shape with the post-treatment shape of the first casting, and then identifying a dimensional distortion in the first casting.

[0007] When the correctable dimensional distortions in the first casting are the result of inadequate support or positioning during the thermal treatment protocol, the method can continue with the steps of obtaining a second support fixture including an open lattice having a plurality of top edges that together define a second open support surface that is different from the first support fixture, applying the thermal treatment protocol to a second casting supported on the second support fixture, capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape, comparing the baseline shape of the second casting with the post-treatment shape, and identifying a reduction in the dimensional distortion in the second casting to verify that the dimensional distortion is at least partially due to inadequate support or positioning during the thermal treatment protocol.

[0008] Alternatively, when the correctable dimensional distortions in the first casting are the result of high gas content in the alloy material, the method can continue with the steps of applying a second thermal treatment protocol to a second casting supported on the support fixture, capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape, comparing the baseline shape of the second casting with the post-treatment shape, and identifying a reduction in the dimensional distortion in the second casting to verify that the dimensional distortion is at least partially due high gas content in the alloy material. In one aspect the second thermal treatment protocol further comprises reducing the period of time that the second casting experiences temperatures that are above a predetermined silicon solution temperature of the alloy material.

[0009] These and other aspects, features, and advantages of the methods of this disclosure will become apparent to the skilled artisan upon review of the detailed description set forth below taken in conjunction with the accompanying drawing figures, which are briefly described as follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is perspective view of a thin-wall aluminum alloy casting, as known on the art.

[0011] FIG. 2 is top view of a flat casting support tray, as known in the art.

[0012] FIG. 3 is a perspective view of a representative HPDC aluminum alloy casting to which the various thermal treatment methods or embodiments of the present disclosure may be applied.

- [0013] FIG. 4 is a perspective view of a plurality of the castings of FIG. 3 supported atop a casting support system, in accordance with a representative embodiment of the present disclosure.
- [0014] FIG. 5 is perspective view of the casting support system and a casting shown in outline, in accordance with another representative embodiment.
- [0015] FIG. 6 is a cross-sectional side view of the casting support system and casting of FIG. 5, as viewed from section line A-A.
- [0016] FIG. 7 is a perspective view of the casting support system of FIG. 5, as viewed from the opposite side.
- [0017] FIG. 8 is a close-up of one end of the cross-sectional side view of FIG. 6.
- [0018] FIG. 9 is a top view of a casting support system, in accordance with another representative embodiment.
- [0019] FIG. 10 is a schematic cross-sectional side view of the casting support system of FIG. 9, as viewed from Section Line B-B.
- [0020] FIG. 11 is a schematic cross-sectional side view of the casting support system of FIG. 9, as viewed from Section Line C-C.
- [0021] FIG. 12 is a temperature vs. time graph of the temperature experienced by an aluminum alloy casting during a thermal treatment protocol, in accordance with another representative embodiment of the present disclosure
- [0022] FIG. 13 is a side view of the casting of FIG. 3 after passing through a thermal treatment protocol, and with a dimensional displacement contour map being overlaid upon an exterior surface to indicate the location and degree of various thermal treatment-induced dimensional distortions.
- [0023] FIG. 14 is a cut-away side view of the casting of FIG. 13 after passing through a thermal treatment protocol, and with a dimensional displacement map being overlaid upon an interior surface to indicate the location and degree of various thermal treatment-induced dimensional distortions.
- [0024] FIG. 15 is a schematic diagram of a heat treatment system for implementing a portion of the thermal treatment protocol of FIG. 12, in accordance with yet another representative embodiment of the present disclosure.

- [0025] FIG. 16 is a schematic diagram of another heat treatment system for implementing a portion of the thermal treatment protocol of FIG. 12, in accordance with another representative embodiment of the present disclosure.
- [0026] FIG. 17 is a schematic diagram of another heat treatment system for implementing a portion of the thermal treatment protocol of FIG. 12, in accordance with yet another representative embodiment of the present disclosure.
- [0027] FIG. 18 is a schematic diagram of a multi-stage quench system for implementing a portion of a thermal treatment protocol, in accordance with another representative embodiment of the disclosure.
- [0028] FIG. 19 is a temperature vs. time graph representing the temperature change of a casting throughout a multi-stage quenching process of FIG. 18.
- [0029] FIG. 20 is a schematic diagram of another multi-stage quench system for implementing a portion of a thermal treatment protocol, in yet accordance with another representative embodiment of the disclosure.
- [0030] FIG. 21 is a schematic side view of a forced air quench system for implementing a portion of a thermal treatment protocol, in accordance with another representative embodiment of the present disclosure.
- [0031] FIG. 22 is a schematic side view of another forced air quench system for implementing a portion of a thermal treatment protocol, in accordance with yet another representative embodiment of the present disclosure.
- [0032] FIG. 23 is a cross-sectional schematic illustration of the flow of thermal fluids impinging on the casting carried by the casting support system of FIG. 6 during a portion of a thermal treatment, in accordance with yet another representative embodiment.
- [0033] Those skilled in the art will appreciate and understand that, according to common practice, various features of the drawings discussed below are not necessarily drawn to scale, and that dimensions of various features and elements of the drawings may be expanded or reduced to more clearly illustrate the embodiments of the present disclosure described herein.

DETAILED DESCRIPTION

[0034] The following description is provided as an enabling teaching of exemplary embodiments of methods and systems for improving the thermal treatment of castings for enhanced metallurgical properties. Those skilled in the relevant art will recognize that changes can be made to the embodiments described, while still obtaining the beneficial results. It will also be apparent that some of the desired benefits of the embodiments described can be obtained by selecting some of the features of the embodiments without utilizing other features. In other words, features from one embodiment or aspect may be combined with features from other embodiments or aspects in any appropriate combination. For example, any individual or collective features of method aspects or embodiments may be applied to apparatus, product or component aspects, or embodiments and vice versa. Accordingly, those who work in the art will recognize that many modifications and adaptations to the embodiments described are possible and may even be desirable in certain circumstances, and are a part of the invention. Thus, the following description is provided as an illustration of the principles of the embodiments and not in limitation thereof, since the scope of the invention is to be defined by the claims.

[0035] Illustrated in FIGS. 1-23 are several representative embodiments of methods and systems for improving the thermal treatment of castings (e.g. such as solution heat treatment, quenching and aging), and in particular for the improving the thermal treatment of thin wall aluminum alloy castings formed in a high pressure die cast (HPDC) process, so as to provide enhanced metallurgical properties while reducing scrap rates. As described below, the methods and systems of the present disclosure can provide several significant advantages and benefits over other thermal treatment methods and systems for castings, and in particular HPDC castings. However, the recited advantages are not meant to be limiting in any way, as one skilled in the art will appreciate that other advantages may also be realized upon practicing the present disclosure.

[0036] Illustrated in FIG. 1 is an exemplary thin-wall aluminum alloy casting 10, and in particular a shock tower 12 for an automobile suspension system, that is representative of the types of castings with complex shapes that have become increasingly common in recent years. For example, recent advances in casting system design and processes have allowed for the integration of multiple stamped sheet metal parts and fasteners, that were previously manufactured separately and assembled together as a shock tower assembly, into a single complex shock tower casting 12 that is substantially lighter in weight while providing equivalent or improved structural performance. The weight reduction is particularly attractive in electric vehicles for improving battery life. However, these complex, thin-wall aluminum alloy castings 10 can also be expensive to manufacture using the more traditional and expensive casting processes such as sand casting, low pressure die casting, and high vacuum die

casting, due to their greater number of process steps, increased set-up and equipment costs, and limited manufacturing rates.

[0037] The less equipment-intensive high pressure die cast (HPDC) process holds the promise of providing these same complex castings at higher rates and reduced casting costs; however, the HPDC process has its own characteristics and drawbacks. For instance, gases and vaporized liquids that are present within the mold cavity when the molten metal is introduced under high pressure and velocity can often be taken up by the alloy material, resulting in a solidified casting that contains a greater amount of dissolved gases than those formed using other casting methods. These dissolved gases can often be distributed unevenly or irregularly throughout the part, forming regions of increased concentration. The dissolved gases tend to migrate out of solution during heat treatment to form micro-bubbles within the alloy material that, in low concentrations, are relatively innocuous. In regions of increased concentration, however, the micro-bubbles can combine during prolonged periods at elevated temperatures to form, depending their location within the structure of a particular casting, laminar cracking defects and blisters near the surface that mar its finish, as well as larger bubbles or porosity internal to the casting that can manifest as more remote and generalized dimensional distortions at the outer surfaces. While the surface defects are generally easy to view and identify, it can be difficult to distinguish dimensional distortions resulting from interior porosity from dimensional distortions resulting from inadequate support or positioning during the thermal treatment protocols described above. This can be particularly problematic for thin-wall castings having complex shapes, such as the shock tower 12 shown in FIG. 1.

[0038] FIG. 2 is an illustration of a general-purpose casting tray 20 of a type commonly-known in the art for supporting castings as they are carried through a thermal treatment furnace, and possibly through the subsequent quenching and aging stages as well. Such casting trays 20 are typically engineered and designed to support one or more castings at a time while repeatedly undergoing the same thermal cycles which the castings only experience once. As can be seen, these casting trays 20 generally comprise a plurality of thick-walled ribs 22 made from a variety of materials, including cast iron, carbon steel and alloys thereof, ceramics, graphite, and the like, and which are spaced apart and interconnected to form apertures 24 that allow the thermal fluids to pass easily through the tray either before or after contacting the supported castings. The casting trays 20 can often include additional structural features, such as the thick-walled circles 23 at the intersections of the ribs, that reduce dimensional distortion of the tray over time and use. It is understood that the general purpose casting trays 20 are often intended to carry a variety of different type castings through their useful life, with the upper edges 26 of the ribs 22 and circles 23 defining a planar, non-continuous upper support surface 28 upon which the castings can be placed prior to introduction into a thermal treatment process.

[0039] According to common practice, the castings will generally be placed on the support surface 28 of the casting tray 20 in their most stable orientation so that they will not shift, roll, or slide off the support tray while the passing through a heat treatment furnace, as it can be prohibitively expensive to shut down a heat treatment furnace during a product run and allow it to cool in order to retrieve a fallen casting. This type of casting support system 20 has been proven effective over time for many types of castings, include heavy or thick-wall castings such as engine blocks, head covers, and transmission casings, that are self-supporting and readily exposed atop the upper support surface 28. For complex thin-wall castings, however, such as the shock tower 12 shown in FIG. 1, the most stable orientation may not provide adequate support for all portions of the casting as the part is raised above a softening temperature, thereby allowing portions of the part to sag or deflect under its own weight. In addition, the most stable orientation may also position the part in a way that hinders or prevents the applied thermal fluids from reaching certain portions of the casting, resulting in large temperature gradients through the thickness or across the expanse of the alloy material during thermal treatment. As described above, it is possible for either situation to result in dimensional distortions that may cause the part to be scrapped.

[0040] FIG. 3 is a perspective view of exemplary thin-wall aluminum alloy casting 100 to which the various methods or embodiments of the present disclosure may be applied, so as to improve the thermal treatment of the casting 100 for enhanced metallurgical properties. This representative high performance production casting 100 can be formed in a high pressure die cast (HPDC) process, and can include a number of thin wall portions 103, thick wall portions 105, apertures 107, as well as a variety of complex surface features such as stiffening ribs 109. In the orientation shown in FIG. 3, the casting 100 can further include a outside or topside surface 104 and an interior or underside surface 106.

[0041] In one aspect the casting 100 of FIG. 3 can designed and configured for use as a shock tower 102 in a vehicle suspension system. However, the methods of the present disclosure are not limited in application to shock towers, to HPDC components intended for the automobile industry, or even to castings formed in an HPDC process. Instead, it will be appreciated that the methods of the present disclosure can be applied to a wide variety of high casting parts intended for use in a wide variety of industries, including but not limited to transportation-based industries such as automobiles, aerospace, railway and shipping, process-based industries such as oil and gas, chemical, and paper making, power generation industries such as coal, oil, natural gas, wind, solar, nuclear and geo-thermal, and the like.

[0042] In general, the casting 100 can be of a type intended for high volume production using a manufacturing process that includes initial formation in an HPDC process, followed by one or more thermal treatments to provide the parts with a desired range of metallurgical properties necessary for

structural performance in a particular application. Prior to commencement of full-scale production, however, it may be desirable to determine both a thermal treatment protocol and a casting support configuration for the castings 100 that will reduce or mitigate the above-described problems with the HPDC process, and thereby produce cast parts with enhanced metallurgical properties at reduced scrap rates, and with improved yield ratios and efficiency. Alternatively, it may be desirable to improve or update an existing high volume production run of the castings 100 for the same reasons.

[0043] Toward those ends, one method of the present disclosure can commence with obtaining a plurality or sample set of untreated test castings 100 of a given production casting design (i.e. the shock tower 102). In one aspect this could be a set of prototype castings that are formed during development of the dies that will be used during full-scale production, while in another aspects the sample set of test castings 100 can be production castings that have been withdrawn from an existing manufacturing process prior to a heat treatment stage. In either case the castings 100 are allowed to cool or rest for a period of time within a temperature controlled environment, and to reach a state of thermal equilibrium at a predetermined measurement temperature that is generally near or at ambient or room temperature.

[0044] Upon reaching thermal equilibrium at the measurement temperature, digital three dimensional (3D) measurements of the full surface geometry of the exterior surfaces of the test castings 100 can then captured and stored in digital format in the memory of an electronic processor-based computer system. One such measurement system for capturing the 3D surface measurement is the ATOS Triple Scan™ surface measurement system provided by GOM mbH™, headquartered in Braunschweig, Germany. Generally, 3D measurements of both the topside exterior surfaces 104 and underside exterior surfaces 106 of the test castings 100 can be captured, processed and stored to determine a digitized three dimensional baseline exterior shape for the castings in the sample set. In some aspects any internal cavities or volumes that are of sufficient size and with sufficient access to receive the sensing head of the measurement system can also be captured and stored in the computer system. Furthermore, in one aspect the three dimensional surface measurement for each of the untreated test castings 100 can also be compared to identify and compensate for any inconsistencies in the casting process.

[0045] The method further includes obtaining a customizable support fixture that is configured to support the castings 100 with a first support profile within one or more thermal treatment zones or systems. One embodiment of a casting support system 110 that includes a customizable support fixture 140 is illustrated in FIG. 4. The casting support system 110 generally includes a base frame or tray 120 having a thickness and top surfaces 122 that define a horizontal base plane 124. The tray 120 also includes a plurality of vertically-aligned tray apertures or openings 126 through the thickness 128 of the tray that allow for thermal fluids such as heated air, cooling air, water, oil, and the like to pass

unobstructed through the base plane 124 of the tray to impinge upon one or more castings 100 that are supported above the base plane 124. The thermal fluids can pass through the tray openings 126 before or after encountering the castings 100, depending on whether the thermal fluids are applied from below, from above, or laterally inward toward the sides of the castings. In one aspect the tray 120 can comprise a perimeter frame 130 having a pair or pairs of side bars 132 that are joined together by a pair of end bars 134 and one or more crossbars 36 extending between the side bars intermediate the end bars 134, and which together define the tray openings 126 interior to the perimeter frame 130. The various components that form the tray 120 can be manufactured from a structural steel material.

[0046] It will be appreciated that the tray 120 is generally configured to ride on chains, a roller conveyor, or similar transfer mechanism while carrying the castings 100 through one or more thermal treatment zones, such as a furnace, a quench system, an oven, or the like, to expose the castings to the thermal treatments. In some embodiments the tray 120 can be used within a continuous process in which multiple trays 120, each supporting a group of castings 100, are carried in sequence through the thermal treatment zones. In some aspects the tray 120 can ride directly on the rollers or chains, while in other aspects the tray can include an underlying support structure (not shown) that provides an interface between the transfer mechanism and the tray 120. In other embodiments where the thermal treatments are applied in discrete batch-type furnaces or quench systems, the trays 120 may be adapted for conveyance by robotic arms, fork lift trucks, shuttle carts, or similar manipulators that move the trays and groups of castings between thermal treatments.

[0047] The casting support system 110 further includes one or more customizable support fixtures 140 attached to the tray 120 that support and align the castings 100, such as the exemplary automotive vehicle shock towers 102 shown in the FIG. 3, in space above the one or more tray openings 126. Each support fixture 140 generally comprises a plurality of support plates 142 that are oriented vertically with lower portions 144 that extend across the tray opening 126 and top edges 146 that extend above the tray opening 126, with the top edges 146 of the support plates 142 having shaped profiles that extend along the lengths of the support plates. In one aspect each of the support plates 142 can intersect with at least one other support plate to form an open lattice 150 having a plurality of top edges that together define an open support surface, or support profile, that is substantially complementary or conforming with the underside surface of the casting 100, as shown in the drawing. However, in other aspects (not shown) the support plates may not intersect with one another, and instead can be aligned in another configuration, such as parallel, non-intersecting rows that are coupled together with beams or brackets, to define the open support surface. The various components that form the support fixture 140, and especially the top edges of the support plates 142 that contact the casting 100, can be made from a stainless steel material.

[0048] Although not limited to any particular type of casting, the casting support system 110 can be particularly suitable for supporting thin wall aluminum alloy castings that have been formed in an HPDC process by reducing many of the problems associated with the thermal treatment of these parts described above. For instance, the customizable support fixtures 140 can be configured to support each casting 100 at key locations during high temperature solution heat treatments while still providing direct access by the thermal fluids to nearly all of the surfaces of the casting. In this way the casting support system 110 can prevent sagging while facilitating uniform and evenly-applied thermal treatments that reduce the internal temperature gradients across the treated part as the overall temperature of the part is being raised or lowered

[0049] Additional aspects of the casting support system 210 can be seen in FIGS. 5-8, in which another customizable support fixture 240 has been individually configured to securely engage with and support a different uniquely-shaped casting 200 (such as a thin wall aluminum alloy HPDC shock tower 202 for another vehicle, shown in outline in FIG. 5) in space above the tray opening 226. As indicated above, the support fixture 240 can support the casting 200 in a manner that allows the thermal fluids to have direct access to nearly all of the surfaces of the casting 200, and especially the underside surfaces 206 that might otherwise be blocked by the tray 220 or the support fixture 240. In addition, the fixture 240 can also orientate the casting 200 in the space above the tray opening 226 to align portions of the casting's topside surfaces 204 and/or underside surfaces 206 with the flow of the impinging thermal fluids, so as to better impart heat into or extract heat away from the alloy material of the casting 200 in a uniform manner.

[0050] As illustrated in the cross-sectional side view of the casting support system 210 and casting 200 provided in FIG. 6, in some applications the casting 200 can include a highly-irregular and complex shape, as shown by the irregular profiles of the topside surface 204 and underside surface 206 along the length of the cross section. In addition, the thickness of the casting 200 between the topside and underside surfaces can also vary considerably along the cross section, resulting in thin-wall portions 203 that can be rapidly heated or cooled, and relatively thicker-walled portions 205 or structurally-dense and heavy portions 207 that require more heat input or extraction to achieve a targeted change in temperature. It will be appreciated that if a similar part were simply placed on a flat top surface of a general purpose casting tray (such as the casting tray 20 shown FIG. 2), the heavier thick-wall portions of the casting are likely to be elevated and supported by thin-wall portions. Consequently, when the yield strength of the alloy material is reduced in a heat treatment process because of softening at solution temperature, the thin wall portions may not be sufficiently strong to support the weight of the heavier portions of the casting without deflection and deformation.

[0051] The casting support system 210 of the present disclosure can overcome this difficulty by independently supporting each section of the casting, including each of the heavy portions 207 or thick wall portions 205 as well as the thin wall portions 203, at key locations 248 across the underside of the casting 200. This can be accomplished by providing the top edges 246 of the support plates 242 with irregular shape profiles along their lengths that are at least partially complimentary with the irregular underside surfaces 206 of the casting. Once the support plates are assembled, and optionally interconnected, together to form the lattice 250, the plurality of top edges 246 of the lattice 250 define an open support surface, or support profile, that is substantially complementary with, although not necessarily conforming to, the underside surface 206 of the casting. As will be understood one of skill in the art, the support surface is “open” because it is not continuous, and instead is only defined by the top edges 246 of the support plates 242 that form a pattern or grid of narrow contact lines underneath the casting. The remainder, majority portion of the “surface” is imaginary and open to the polygonal-shaped flow areas or channels defined by the vertical support plates, and that can guide separate flows of thermal fluid upward from the tray opening 226 to the underside surface 206 of the casting 200.

[0052] The support surface defined by the plurality of top edges 246 of the support plates 242 can be substantially complimentary with the underside surface 206 of the casting 200 in that the casting may only fit atop the lattice 250, or become securely engaged by the lattice, in a single position. This engagement with the lattice can include multiple contact locations 248 having both vertical components that bear the weight of the castings and horizontal components that prevent the casting from moving or shifting laterally. Thus, once the casting 200 is settled into position atop the support fixture 240, it can be securely maintained in that position as the casting tray 220 is moved through one or more thermal treatment sections and subjected to a variety of applied loads by the impinging thermal fluids. For example, the casting support system 210 can facilitate the use of directed streams of high velocity thermal fluids during thermal treatments, including but not limited to jets of high pressure air or water during a quench cycle, that would tend to reposition or shift parts that are less securely supported on a casting tray.

[0053] Nevertheless, even though the support surface defined by the plurality of top edges 246 of the support plates 242 may be substantially complimentary with the underside of the casting 200, it need not be exactly conforming with the underside surface 206 along the length of the support plates 242. The support surface can instead include discrete contact locations 248 separated by gaps 247 where the top edges 246 are spaced from the underside surface 206 by a distance that is sufficient to allow thermal fluids to flow between the two surfaces. In one aspect the contact locations 248 between the lattice 250 and the underside 206 of the casting 200 can be judiciously located at predetermined key locations across the expanse of the underside surface that would otherwise be prone to sagging or

distortion if not directly supported by the support fixture 240. In this way the casting 200 can be supported in space above the opening 226 using a reduced number of key contact locations 248, while leaving the remainder of the casting surfaces directly accessible by the thermal fluids.

[0054] Also shown in FIG. 6 is a stationary thermal treatment zone 290 having an upper plenum 294 having downwardly-directed nozzles 295 or outlets for creating one or more downwardly-directed flows 296 of a thermal fluid (e.g. heated air in a heat treatment zone or cooling air in a quench zone) that impinge on the exposed topside surfaces 204 of the casting 200, as well as a lower plenum 297 having upwardly-directed nozzles 298 or outlets for creating one or more upwardly-directed flows 299 of the thermal fluid that impinge on the exposed underside surfaces 206 of the casting 200. In addition, the customizable fixture 240 that supports the casting 200 is itself coupled to a tray 220 that is carried on the rollers 292 of a roller conveyance system through the thermal treatment zone 290. In one aspect both the downwardly-directed flows 296 and the upwardly-directed flows 299 can be substantially aligned with the thick-walled portions 205 and the structurally-dense portions 207 of the casting 200 so that more heat can be imparted into or extracted from these portions of the casting than the immediately adjacent thin-wall portions that require less heat transfer to achieve the same change in temperature. Furthermore, in one aspect the support surface defined by the plurality of top edges 246 of the support plates 242 can position and orientate the casting 200 in space to align the thick-walled portions 205 and the structurally-dense portions 207 with the both sets of nozzles 295, 298. In addition, the upwardly-directed flows 299 of thermal fluid can pass substantially unimpeded through both the tray opening 226 and the lattice 250 of intersecting support plates 242 to impinge against the underside surfaces 206 of the casting 200.

[0055] FIG. 7 is a perspective view of the casting support system 210 of FIGS. 5-6 without the casting, and illustrates the customizable fixture 240 that is formed by, in this case, four intersecting vertical support plates 242 mounted to the tray 220 above the tray opening 226. As can be seen, in this embodiment the perimeter frame 230 of the tray 220 can include multiple pairs of side bars 232 with cylindrical cross-sections, that are coupled at their ends to end bars 234 or crossbars 236 with rectangular cross-sections, and which together define a plurality of tray openings 226 interior to the perimeter frame 230. In one aspect the side bars 232, end bars 234 and crossbars 236 can be sized and configured together to form a standardized tray 220 that can serve as a base frame with standardized dimensions, so that a variety of differently-configured fixtures 240 can be removably and interchangeably mounted over the tray openings 226. In addition, the underside surfaces of the perimeter frame 230 and cross-bars 236 can ride directly atop the rollers 292 of the conveyance system (FIG. 6), and in one aspect can be removably coupled to each other to form a modular tray 220 that can be lengthened or shortened according to a desired application, and in which a damaged side

bar or end bar/crossbar can be individually removed and replaced with an undamaged component without having to replace the entire tray 220.

[0056] The customizable fixture 240 of representative support system 210 can comprise four support plates 242 that are oriented vertically with lower portions 244 that extend across the tray opening 226 and top edges 246 that extend above the tray opening 226, and together form a lattice structure 250 in which the top edges 246 define the open support surface, or support profile, for the casting. In one aspect the support plates 242 can be substantially aligned with the major horizontal axes 212, 216 of the perimeter frame 230, with the lower edges 244 extending across the length or the width of the tray opening 226. In another aspects (not shown) the support plates can be aligned on the diagonal or at another angle relative the major horizontal axes of the perimeter frame 230. For the two support plates 252 of representative fixture 240 that are aligned parallel with the longitudinal axis 212 of the perimeter frame 230, the lower ends can terminate with notches 253 that engage the inner edges of the rectangular end bars 234 and crossbars 236, and may not extend across the centerlines of the crossbars 236 so as to not interfere with a fixture overlying the adjacent tray opening. For the two support plates 256 that are aligned parallel with the width axis 216 of the perimeter frame 230, the lower ends can extend outward past the side bars 232 and can include notches 257 formed into their lower edges that engage with mounting bars 238 that extend upward from the upper surfaces of the cylindrical side bars 232.

[0057] In one aspect the support plates 242 can intersect and connect with each other at predetermined locations defined by upwardly-opening half-slots formed into a lower pair of support plates 252 that mate with downwardly-opening half-slots formed into an upper pair support plates 256, as known in the art. In this way the support plates 242 of the support fixture 240 can become interlocked together to form the lattice 250 prior to attachment to the tray 220. Furthermore, and as described in more detail below, the positions of the interlocking support plates 252, 256 within the lattice 250 can be modified relative to each other and to the surrounding structure of the tray 220 in order to re-position the contact locations 248 of the top edge 246 underneath the portions of the casting that require the most support. In the illustrated embodiment this can be accomplished by adjusting the locations of the half-slots along the lengths of the support plates, and with the ends of the support plates being moved a corresponding distance along the end bars 234 or crossbars 236 or along the mounting bars 238 atop the side bars 232. Nevertheless, it will be appreciated that other connection methods or mechanisms for connecting the support plates 242 to each other and to the tray 220 are also possible and considered to fall within the scope of the present disclosure.

[0058] Also visible in FIGS. 5-7 are the plurality of apertures 245 that can be formed through the thickness of the support plates 242 that allow the thermal fluid to flow crossways through the support plates. As shown in FIGS. 5 and 7, in one aspect the apertures 245 can be elongated in the direction of the vertical axis 218 of the support system 210. This can result in a lattice support structure 250 that is largely “transparent” to the upwardly-directed flows of thermal fluid due to the minimal amount of flat surface areas and corners oriented perpendicular to the path of the thermal fluid that could obstruct its passage and diminish its velocity. In another aspect of the support fixture 240 shown in FIG. 6, however, the apertures 245 in the vertically-aligned support plates can be elongated in the direction of the major horizontal axes 212, 216 of the support system 210. This can result in a support structure 250 with a much larger amount of flat surface areas and corners oriented perpendicular to the path of the thermal fluid, thereby creating a greater degree of obstruction to the upwardly-directed flow of thermal fluid that can reduce its velocity while increasing its turbulence and mixing. It will be appreciated by the skill artisan that, depending on the application, both options could be used to provide for an improved transfer of heat into or away from the underside surfaces of the casting.

[0059] Castings 200 that are similar to the thin wall aluminum alloy HPDC shock tower 202 shown in FIGS. 5-6 can often include thin-wall projections of alloy material that project outwardly to define an outer edge 209 or flange (FIG. 5). These thin wall structures that are unsupported along one side can often be more susceptible to deflection or deformation during thermal treatments, and can therefore require a greater degree of support or constraint than other thin-walled internal sections of the casting that are substantially surrounded by alloy material. To provide this extra support, in one aspect the ends of the support plates 242 can include upwardly extending projections 249 that bound the outer edges 209 of the casting.

[0060] FIG. 8 is a close-up view of the left-side end of the support plate 242 of FIG. 6, and illustrates the upwardly extending projection 249 that bounds one outer edge 209 of the casting 200. In one aspect the lower inside edge of the projection 249 can include a notch 255 that is sized to receive the outer edge 209 of the casting after accounting for the thermal growth of both the casting and the support plate during a heat treatment. In addition, the top edge 246 of the support plate 242 can provide an extended line of contact at the contact location 248 along the underside surface 206 of the thin-wall portion 203 of the casting proximate the outer edge 209. It will be appreciated that both the extended line of contact that defines the proper position of the thin-wall portion 203 and/or the notch 255 that constrains the outer edge 209 from pulling upward during heat treatment can serve to maintain the alignment and prevent deformation of the outer edge portions of the casting during a plurality of thermal treatments.

[0061] The support fixture 240 illustrated in FIGS. 5-7 can engage with the casting 200 along both the underside surfaces 206 and the outer edges 209 to securely support the casting 200 in a single position and to prevent it from accidentally becoming dislodged from the fixture during thermal treatment. In other embodiments, such as casting support system 110 illustrated in FIG. 4, the support fixture 140 can engage with the casting 100 primarily along its underside surfaces to securely support the casting in a single position, without necessarily engaging an outer edge.

[0062] FIG. 9 is a top view of another representative embodiment of the casting support system 310 that also includes a fixture 340 comprising four vertically-aligned and intersecting support plates, with two of the support plates 352 extending parallel to the longitudinal axis 312 of the base tray 320 and two support plates 356 extending parallel to the width axis 316 of the base tray 320. When assembled, the support plates 352, 356 together define nine polygonal shaped flow channels 360 that can guide flows of thermal fluid upward from the tray opening 326 to the underside surface of the casting (not shown). In this embodiment one of more support plates can also include a deflector 362, 366 that extends outward into a channel to redirect the flow of thermal fluid toward an opposing support plate. In one aspect the deflector 362 can extend outward and upward in the direction the flow 363 to redirect the flow toward the opposite side of the same channel, as shown in the cross-sectional schematic view of FIG. 10. In another aspect the deflector 366 can extend outward and downward against the direction the flow 367 to redirect the flow through an aperture 368 in the support plate and toward the opposite side of an adjacent channel, as shown in the cross-sectional schematic view of FIG. 11.

[0063] Additional detail and information regarding the casting support system disclosed above can be found in co-owned and co-pending U.S. Provisional Patent Application No. 62/222,407, filed September 23, 2015, and entitled SYSTEM FOR SUPPORTING CASTINGS DURING THERMAL TREATMENT, which application is incorporated by reference in its entirety herein.

[0064] As described above in reference to FIGS. 3-4, the methods of the present disclosure generally include obtaining one or more support fixtures 140 having support profiles configured to initially support the castings 100 within one or one thermal treatment zones or systems. In one aspect each initial support profile is defined by an open lattice 150 of the support fixture 140 formed from a plurality of support plates 142, with the top edges of the support plates together defining an open support surface that is substantially complementary with the underside surface 106 of the casting 100, and that is configured to loosely support the casting 100 atop the lattice 150 in an initial position and orientation in space above a tray opening 126. In addition, the open support surface can further include of plurality of discrete, predetermined contact locations separated by gaps where the top edges of the support plates 142 are spaced from the underside surface 106 of the casting 100, so as to allow direct access for thermal fluids to nearly all of the underside surface 106. Although shown as a group

of four support fixtures 140 supporting four test castings 100 on a single casting tray 120, it will be appreciated that the desired testing can be conducted with fewer support fixtures 140 and castings 100, so as to perform the test cycles in a more economical fashion. Once the baseline surface measurements for the aluminum alloy castings 100 have been captured in three dimensions and the initial or first support fixtures obtained, an initial or first thermal treatment protocol can be applied to one or more test castings 100 that are supported on the support fixture 140.

[0065] In one aspect of the present disclosure shown in the temperature vs. time graph of FIG. 12, the thermal treatment protocol 400 can include three separate thermal treatment stages, namely a first heating stage 420, a second heating stage 430, and a quenching stage 440. The first heating stage 420 comprises a first period of time (t1) 424 from when the casting enters a furnace and is heated from an initial temperature 421 to a first casting temperature 425 that is less than a predetermined solution temperature 414 of a silicon component of the aluminum alloy, yet without reaching or exceeding the predetermined silicon solution temperature 414. For example, and without being bound to any particular theory, it is contemplated by the present inventors that the internal “pore-making” process that leads to the formation and expansion of the internal pores or gas bubbles within the castings begins with the silicon component of the aluminum alloy being taken into solid solution as the casting reaches the silicon solution temperature. As the silicon is taken into solution, the size of the silicon particles appears to shrink as the overall number of silicon particles appears to grow, thereby allowing the entrained gases within the casting to migrate throughout the material. Eventually, however, the trend reverses as the smaller silicon particles grow together into larger particles that hinder or dam the migration of the gas. The entrapped gas then combines together into bubbles or pores that will continue to grow for as long as the casting is maintained at an elevated temperature. If left unchecked, the enlarged bubbles or pores near the surface can break through the surface as blisters, while the enlarged bubbles or pores internal to the casting can cause dimensional distortions.

[0066] It is also theorized that because the solution temperature of the silicon component is distinguishable from and less than the solution temperatures of the one or more metal alloying components, the solutionizing heat treatment of the aluminum alloy that ultimately results in the desired improvements in mechanical properties may not begin until the castings are heated to their alloying metal solution temperature. Thus, by recognizing and taking into consideration the differences between the silicon solution temperature and the alloying metal solution temperature, it is further contemplated that the time (t3) 436 spent by the castings at or above both the solution temperature 414 of the silicon component and the solution temperature 418 of the metal alloying component, prior to quenching, can be controlled to produce aluminum alloy castings having superior mechanical properties at reduced scrap rates, and with the castings having a substantial reduction in

dimensional distortions that would otherwise result from the formation of enlarged bubbles of entrapped gases.

[0067] It will be appreciated that both the time duration (t1) 424 and the first heating rate 422 of the castings in the first heating stage 420 can vary substantially between different embodiments of the thermal treatment protocol 400. For reference purposes, the rise/run of the first heating rate 422 is defined as °C/min, and can be applied as an instantaneous heating rate or as an average heating rate during a specified period of time, such as, for example, the entire first heating stage 420 or a merely a portion of the first heating stage 420. Factors that affect the duration (t1) and/or the first heating rate 422 can include the type and configuration of the furnace, the initial temperature 421 of the castings when the castings first enter the furnace, the thickness and/or the surface area exposure of the castings, and the like.

[0068] For instance, in some embodiments a casting may be quite thick, such as the casting for an engine block. It may also be preferable, moreover, for substantially all of the material of the thick casting to reach the first casting temperature 425 prior to entering the second heating stage 430. In such embodiments, the targeted heating profile may be achieved by heating the casting at a slower rate and then allowing the casting to soak at the first casting temperature 425 for a few minutes (e.g. 2-5 minutes or similar extended time period) toward the end of the first heating stage 420 to provide ample time for the heat to become evenly distributed throughout the casting. In other embodiments the casting may be a thin-walled structure with a greater proportion of exposed surface area that readily receives and distributes the applied heat to reach thermal equilibrium at the first casting temperature 425 in a much shorter period of time, in which case the thermal soaking period may be reduce or eliminated.

[0069] In other aspects, such as the embodiment shown in FIG. 12, the castings may be heated at a substantially constant first heating rate 422 throughout a majority portion of the first heating stage 420, followed by a gradual tapering of the rate of heating toward the end of the first heating stage as the castings approach the intended first casting temperature 425. This technique can provide better control of the thermal treatment protocol and ensure that the temperature of the castings does not inadvertently overshoot the first casting temperature 425 and encroach or reach the predetermined silicon solution temperature 414 while the castings remain in the first heating stage 420, and thereby prematurely trigger the pore-making process described above.

[0070] In yet other aspects of the present disclosure, the first heating stage of the furnace can be maintained at a substantially constant first stage temperature that is greater than the first casting temperature 425, so as to maintain the flow of heat into the casting throughout the first heating stage 420. In embodiments where first stage temperature is greater than the predetermined silicon solution

temperature 414 at which the silicon component rapidly enters into solid metal solution, the movement of the castings through the furnace can be timed so that the castings reach the first casting temperature 425 and exit the first heating stage 420 prior to reaching the predetermined silicon solution temperature 414 or thermal equilibrium with the first stage temperature. In embodiments where the first stage temperature is less than the predetermined silicon solution temperature 414, the time duration (t1) 424 of the castings within the first heating stage 420 can be extended so that the castings approach thermal equilibrium with the first stage temperature simultaneous with reaching the first casting temperature 425.

[0071] Accordingly, in one aspect the first stage temperature of the first heating stage can be maintained within about 10 °C, plus or minus, of the predetermined silicon solution temperature 414. In another aspect the first stage temperature of the first heating stage 420 can be maintained at a temperature that is greater than 10 °C above the predetermined silicon solution temperature 414, so as to provide an increase in the first heating rate 422 throughout the first heating stage 420 with a corresponding decrease in the time duration (t1) 424 of the first heating stage, and which can further include accurate control of the movement of the castings through the first heating stage 420 to ensure that the castings exit the first heating stage 420 prior to reaching the predetermined silicon solution temperature 414.

[0072] Upon reaching the first casting temperature 425 at the end of the first heating stage 420, the castings can then transition or move into the second heating stage 430 of the thermal treatment protocol 400 that generally comprises a second period of time (t2) 434 extending from the entrance of the castings into the second heating stage 430 until their exit and movement into the quench stage 440. Upon entry into the second heating stage 430, the castings are quickly heated from the first casting temperature 425 to a second casting temperature 435 that is greater than or substantially equal to the predetermined alloying metal solution temperature 418. The castings can then be maintained at the second casting temperature 435 for the remainder of the time period (t2) 434 of the second heating stage 430 in a substantially isothermal (i.e. constant temperature) portion 437 of the protocol 400. Depending on the time taken to heat the castings from the first casting temperature 425 to the second casting temperature 435 after entry into the second heating stage 430, the substantially isothermal portion 437 of the thermal treatment protocol 400 at the second casting temperature 435 can typically range from about 10 minutes to about 20 minutes. Nevertheless, substantially isothermal portions 437 that are less than 10 minutes in duration, such as between 5 minutes and 10 minutes in duration, are also possible and considered to fall within the scope of the present disclosure.

[0073] In one aspect the second casting temperature 435 can be between about 5 °C and 10 °C above the predetermined solution temperature 418 of the metal alloying component, in order to ensure that the metal alloying component in all portions of the casting reaches or exceeds the alloying metal solution temperature and enters into solid solution, but without excessively exceeding the alloying metal solution temperature in ways that could lead to detrimental side effects. In other aspects, such as when the alloying metal solution temperature is precisely known and the thermal treatment protocol 400 can be tightly controlled, the second casting temperature 435 can be 5 °C or less above the predetermined solution temperature 418 of the metal alloying component.

[0074] As illustrated in FIG. 12, in one aspect the heating of the castings in the second heating stage 430 can involve an initial or second heating rate 432 that is sharply increased over the rate of heating the castings in the first heating stage 420 immediately prior to entering second heating stage 430. This can result in a step increase in the temperatures of the castings to the second casting temperature 435 within a shortened period of time, with the temperature 412 of the castings reaching the predetermined silicon solution temperature 414 within seconds of entering the second heating stage 430. For example, while it can typically take 3 to 5 minutes at the initial or second heating rate 432 for the castings to reach the predetermined alloying metal solution temperature 418, the temperature of the castings can nevertheless reach and exceed the predetermined silicon solution temperature 414 shortly after entering the second heating stage 430. Indeed, and especially in cases when the first casting temperature 425 at the end of the first heating stage 420 is within a few degrees of the predetermined silicon solution temperature 414, the temperature of the castings can reach and exceed the predetermined silicon solution temperature 414 within 60 seconds or less of entering the second heating stage 430. Thus, in one aspect, the time that the castings spend above the predetermined silicon solution temperature 414 can be substantially equal to the time (t_2) 434 spent within the second heating stage 430, which feature can be used to simplify subsequent calculations.

[0075] In addition, the second heating stage 430 of the furnace can be maintained at a substantially constant second stage temperature that is greater than the first stage temperature, so as to maintain the flow of heat into the castings at least during the first portion of the second heating stage 430. In one aspect the additional heat input needed to quickly raise the temperature of the castings to the second casting temperature 435 can be provided by an additional heating apparatus, such as directed heaters or high flow hot air nozzles, that can direct additional heat onto the castings and provide a boost to the initial second heating rate 432. Moreover, the additional heating apparatus can be configured to raise the temperature of the castings to the second casting temperature 435 in a shortened period of time without raising the second stage temperature in the second heating stage portion of the furnace.

[0076] Once the castings reach the second casting temperature 435 that is associated with the substantially isothermal portion 437 of the protocol 400, the second stage temperature can prevent the flow of heat away from the castings for the remainder of the time period (t₂) 434 of the second heating stage 430. In one aspect the second stage temperature can be substantially equal to the second casting temperature 435, while in other aspects the second stage temperature can be marginally higher than the second casting temperature 435 so that the temperature of the castings continues to rise slightly during the remainder of the second heater stage, but typically only a small amount as the time remaining in the second heating stage is relatively short. In one embodiment the second stage temperature can be less than about 10 °C above the predetermined alloying metal solution temperature 418 at which the at least one metal alloying component rapidly enters into solid metal solution.

[0077] In comparing the period of time (t₃) 436 the castings spend at or above the predetermined solution temperature 418 of the metal alloying component with the overall time duration (t₂) 434 of the second heating stage 30, as measured from entering the second heating stage 430 to entering the quench stage 440, the (t₃)/(t₂) timing ratio of the castings at the alloying metal solution temperature 418 can be 50% or greater. This timing ratio can also be known as the time-in-treatment ratio. As will be appreciated by those skilled in the art, the time-in-treatment ratio can be a good approximation of the actual percentage of time that the castings spend in the solutionizing heat treatment at or above the alloying metal solution temperature at which the metal alloying component rapidly enters into solid metal solution, in addition to being at or above the silicon solution temperature at which the silicon component rapidly enters into solid metal solution. It will also be appreciated that the time-in-treatment ratio provided by the present disclosure can be substantially increased over solution heat treatment methods for HPDC castings currently known and practiced in the art.

[0078] Indeed, depending on the temperature differentials between the predetermined silicon solution temperature 414 and the predetermined alloying metal solution temperature 418 and between the first casting temperature 425 and the predetermined silicon solution temperature 414, as well as the configuration of the furnace, it is contemplated that in some embodiments the (t₃)/(t₂) time-in-treatment ratio of the castings at or above the predetermined alloying metal solution temperature 418 can be greater than 60%, greater than 70%, or even 80% or greater. For example, if it has been determined that the (t₂) value for a particular alloy is limited to 418 minutes in order to avoid the manifestation of blistering and/or dimensional distortion on a high percentage of the castings, a (t₃)/(t₂) time-in-treatment ratio of 75% can ensure that the castings are maintained at or above the predetermined alloying metal solution temperature for about 13.5 minutes. In this way the castings can obtain a substantial increase in the beneficial affects of an alloying metal solutionizing heat treatment while avoiding the harmful effects of the pore-based defects by limiting the time spent at or above the silicon solution temperature.

- [0079] It will thus be appreciated that heating the castings in the first heating stage 420 to a first casting temperature 425 that is near to the predetermined silicon solution temperature 414, can be advantageous for both reducing the heating requirements in the second heating stage 430, and for reducing the time needed to reach the predetermined alloying metal solution temperature 418 as the castings are heated to the second casting temperature 435 in the second heating stage 430.
- [0080] Upon reaching the end of the second heating stage 430, the castings can then transition or move into the quench stage 440 of the thermal treatment protocol 400 in which the castings are quickly cooled from the second casting temperature 435 to a quenched temperature 445 that is generally less than 250 °C but still well above ambient temperature. The quench stage 440 generally comprises a liquid spray cooling system, a forced air or gas cooling system, a liquid immersion cooling system, or combinations of the above. During the quench stage 440 the castings can be cooled at a cooling rate 442 for a time period (t₄) 444 that generally ranges from one to about five minutes. After completion of the quench stage 440, the castings can be removed to ambience and allowed to cool and naturally age for a T4 temper, or to a separate temperature controlled chamber (not shown but known to one of skill in the art) for artificial aging at an elevated temperature for a predetermined period of time to achieve a T6 temper. As will be appreciated by one of skill in the art, other quenching and aging protocols are also possible and considered to fall within the scope of the present disclosure.
- [0081] Additional detail and information regarding the thermal treatment protocol 400 disclosed in FIG. 12 can be found in co-owned and co-pending U.S. Provisional Patent Application No. 62/153,724, filed April 28, 2015 and entitled SYSTEM AND METHOD FOR THERMAL TREATING ALUMINUM ALLOY CASTINGS, which application is incorporated by reference in its entirety herein. It is understood, however, that the thermal treatment protocol 400 described above is merely one exemplary embodiment of the present disclosure, and that other and different thermal treatment protocols may also be applied to the test castings 100 supported on the support fixture 140 (FIG. 4) and are also considered to fall within the scope of the present disclosure.
- [0082] Upon completion of the initial or first thermal treatment protocol, the one or more treated test castings 101 (as opposed to the untreated castings 100 prior to or during thermal treatment) can again be allowed to cool or rest for a period of time within a temperature controlled environment and to reach a state of thermal equilibrium at the predetermined measurement temperature. At this point the method can proceed with capturing a second digitized, three dimensional surface measurement of the test casting 101 to determine its post-treatment three dimensional shape, after which the post-treatment shape can be compared with the baseline shape to determine if the shape of the part changed during the thermal treatment protocol, and if so, at what locations and by how much. As shown in the side view of FIG. 13 and the cut-away side view of FIG. 14, for example, in one aspect this can be

accomplished by electronically combining the digitized baseline shape and digitized post-treatment shape of the casting 101 to form a three dimensional contour map or model 180 of the casting 101 that can illustrate one or more regions 182, 184 of substantial dimensional distortion. If these dimensional changes exceed predetermined tolerances, the method of the present disclosure can then proceed with identifying whether the dimensional distortions 182, 184 are the result of inadequate support during the thermal treatment protocol, improper application of thermal fluids relative to the position and orientation of the casting 101 within the thermal treatment zones, or as a manifestation of significant porosity internal to the casting that is indicative of excessive amounts of dissolved gases within the alloy material. It is understood that combinations of the above sources of distortion are also possible, and that in some cases multiple lines of approach for mitigating the distortions may be required.

[0083] A common indication of high amounts of dissolved gases and porosity internal to the casting are blisters on the exterior surfaces of a treated casting 101, and in one aspect the surface of the treated test casting proximate the dimensional distortions can be inspected to identify surface porosity related to an increased concentration of dissolved gases in the alloy material. It is possible, however, to have internal, localized regions of high gas content causing exterior dimensional distortions without significant accompanying surface blistering or defects. In this case the casting can also be sectioned proximate the dimensional distortion to identify internal porosity related to high gas content in the alloy material.

[0084] If it is determined that the dimensional distortions 182, 184 in the treated test casting 101 are the result of high gas content in the alloy material, in one embodiment the method can continue with the application of a second and different thermal treatment protocol that is intended to eliminate or substantially reduce the development of internal porosity-related distortions within other untreated test castings. For example, to verify that at least of portion of the source for the dimensional distortions is high gas content within the alloy material, the initial or proposed thermal treatment protocol for the untreated castings 100 can be altered by reducing the period of time during which the castings experience temperatures that are above the predetermined silicon solution temperature 414 of the alloy material, as described above in reference to FIG. 12. This can be accomplished in a variety of ways, depending on the type of heat treatment zone or system (i.e. furnace) that is used to apply the first and second heating stages in the thermal treatment protocol.

[0085] As shown in the temperature vs. time plot of FIG. 12, for instance, the castings 100 can pass through a first transition zone 429 when transitioning between the first heating stage 420 and the second heating stage 430, and then again through a second transition zone 439 between the second heating stage 430 and the quench stage 440. The second transition zone 439 will typically comprise the physical movement of the castings from within the furnace to a quench station that is located outside the furnace, such as through a discharge door at the outlet end of the furnace. However, the

first transition zone 429 between the first heating stage 420 and the second heating stage 430 can comprise either movement through a physical barrier or an increase in the heating rate, typically depending on the type of furnace used to perform the heat treatment. As described in more detail below, for example, a process furnace that continuously moves the castings through a heated interior volume on a conveyor system may include an interior door that defines the boundary between the two stages. Alternatively, a batch furnace that heats the castings in place can include additional heaters, high flow hot air nozzles, or similar heating apparatus that can become active at the first transition zone to increase the rate of heating and quickly raise the temperature 412 of the castings from first casting temperature 425 to the second casting temperature 435.

[0086] FIG. 15 is a schematic drawing of one embodiment of a continuous process furnace 450 that includes an endless conveyor chain 452 (i.e. a parallel synchronized pair of chains) running through an insulated enclosure 454, with an intake door 456 at an inlet end and a discharge door 458 at an outlet end. The furnace 450 can further include a number of heating cells 460 aligned in series along the length of the furnace 450, with each heating cell 460 including a heater assembly 462 extending into the cell (for example, extending downward through the ceiling of the enclosure 454) and comprising, for instance, a heater unit and a motor driven blower that drives the heated air downward into the enclosure 454 to flow across and around the castings 405 riding slowly through the furnace on trays that straddle the distance between the individual chains in the conveyor chain 452. Although the process furnace 450 shows seven heating cells 460 arranged along the length of the furnace with each heating cell 460 having its own blower-based heater assembly 462, it will be appreciated that FIG. 15 is a mere schematic representation of one possible configuration of a process furnace 450 or system for implementing a portion of the thermal treatment protocol 400 of FIG. 12, and that a wide variety of heating cell numbers and arrangements, as well as various different types of heater assemblies and technologies, are also possible and considered to fall within the scope of the present disclosure.

[0087] The process furnace 450 can include an internal barrier with a gate or intermediate door 464 that divides the interior of the insulated enclosure 454 into a first heating stage 420 and a second heating stage 430 that coincide with the first heating stage 420 and second heating stage 430 depicted in FIG. 12. As the single conveyor chain 452 passes through both stages to carry the castings 405 through the furnace 450 at a constant speed, it will be appreciated that the speed of the conveyor chain 452, the total length of the furnace enclosure 454, and the position of the intermediate door 464 along the length of the enclosure can determine the time duration (t1) 424 of the first heating stage 420 and the time duration (t2) 434 of the second heating stage 430. In one aspect the time duration (t2) 434 of the second heating stage 430 can be limited to 25 minutes or less, and preferably 20 minutes or less, to ensure that the castings 405 exit the furnace 450 before the development of any pore-based defects.

As a result, the heat output produced by the heating cells 460 in the first heating stage 420 can then be adjusted to heat the castings 405 at a desired first heating rate 422 so that the temperature 412 of the castings 405 reaches the first casting temperature 425 prior to or substantially simultaneous with the castings 405 reaching the intermediate door 464.

[0088] In one aspect the temperature of the first heating stage 420 can be maintained at the first casting temperature 425 and the time duration (t_1) 424 can be extended until thermal equilibrium is gradually established between castings 405 and the heated air in the first heating stage 420. The temperature of the second heating stage 430 can likewise be maintained at the second casting temperature 435, but with the additional heat input at the beginning of the second heating stage 430 to quickly bring the castings into thermal equilibrium between castings 405 and the heated air in the second heating stage 430.

[0089] Also visible in FIG. 15, in one aspect the position of the intermediate door 464 along the length of the furnace enclosure 454 can be changed to better accommodate the desired casting temperature profile for a particular aluminum alloy casting. If, for example, a blank space 466 is provided between each of the heating cells 460 in the center of furnace enclosure 454 and filled with an insulated spacer 467 when not in use, the intermediate door 464 can then be moved upstream or downstream as desired to reassign the adjacent heating cells into the second heating stage 430 or into the first heating stage 420, respectively. This feature can be advantageous over furnaces having an intermediate door in a fixed position by providing the user with an additional variable beyond the speed of the conveyor chain 452 and the output of the heater assemblies 462 for optimizing the (t_3)/(t_2) time ratio in the second heating stage.

[0090] Furthermore, it will be appreciated that the output of the heater assembly in the first heating cell of the second heating stage 430 may not be sufficient to raise the initial or second heating rate 432 to the desired value. In this case one or more additional heating apparatus 468, such as an additional heater or hot air nozzle, can be added to the affected heating cell to direct additional heat onto the castings 405 and provide a boost in the initial or second heating rate 432 that will raise the temperature of the castings to the second casting temperature 435 in a shortened period of time. For furnaces 450 having an adjustable intermediate door 464, empty support fixtures filled with insulating plugs 469 can also be provided at each additional optional location, so that the additional heating apparatus 468 can be repositionable along with the intermediate door 464.

[0091] The process furnace 470 schematically illustrated in FIG 16 illustrates another option for accommodating a desired casting temperature profile for a particular HPDC aluminum alloy casting. Similar to the previous process furnace embodiment, the process furnace 470 generally includes an insulated enclosure 474 with an intake door 476 at an inlet end, an intermediate door 484 that

separates the enclosure into a first heating stage 420 and a second heating stage 430, and a discharge door 478 at an outlet end. The furnace 450 also includes a number of heating cells 480 aligned in series along the length of the furnace 470, with each heating cell 480 comprising a heater assembly 482 extending downward through the ceiling to direct heated air downward into the enclosure 454 to impinge on the castings 405 below that are riding slowing through the furnace on a conveyor system. An additional heating apparatus 488 can also be added immediately downstream of the intermediate door 484 to provide a boost in the initial or second heating rate 432 of the second heating stage 430.

[0092] In this embodiment of the process furnace 470, however, the position of the intermediate door 484 along the length of the enclosure 454 can be fixed and the conveyor system can comprise conveyor chains 472, 473 (i.e. parallel synchronized pairs of chains) having independently controllable operating speeds. The two independently controllable conveyor chains 472, 473 can provide the user with the capability of independently configuring the time duration (t_1) of the first heating stage and the time duration (t_2) of the second heating stage, which in turn can allow for optimization of both the first heating rate 422 and the (t_3)/(t_2) time-in-treatment ratio in the second heating stage 430. In one aspect the two conveyor chains 472, 473 can meet together at the first transition zone 429 (i.e. the intermediate door 484), as illustrated in FIG. 12, while in other aspects the conveyor chains can meet together at another location within the furnace enclosure 474, such as at a location within the second heating stage 430 and downstream of the intermediate door 484 (not shown).

[0093] The solution heat treating system 550 illustrated in the plan view of FIG. 17 can comprise a plurality of batch-type heat treating furnaces 560 aligned side-by-side. Each furnace 560 can include an insulated enclosure 562 with an access door 564 on one side, and with all the access doors 564 facing the same direction. Each of the furnaces 560 can also include at least one primary heater assembly 566 extending downward through the ceiling of the enclosure 562 and comprising, for example, a heater unit and a motor driven blower that drives the heated air downward into the enclosure 562 that is typically sized to receive a plurality of castings 505 that have been loaded onto a tray or rack in spaced-apart and/or stacked relationships, so that the heated air can be substantially uniformly applied to each casting. In one aspect the primary heater assembly 566 can be configured to provide a variable heat output, such as with a variable frequency motor drive 567 that can increase the flow of heated air into the enclosure 562. In another aspect the heat treating furnaces 560 can be provided with one or more additional secondary heaters 568, such as an additional heater or high flow hot air nozzle, to provide a boost to the initial or second heating rate 532 that will raise the temperature of the castings 505 to the second casting temperature 535 in a shortened period of time.

[0094] Also shown in FIG. 17, the solution heat treating system 550 can further include a movable quench station 570 that translates back and forth in front of the access doors 564 (i.e. the second transition zone 539) in each of the furnaces 560 to receive and immediately quench the rack of heated castings after the castings are withdrawn from the furnaces 560. The quench station generally includes an enclosure 572 with at least one opening 574 directed toward the furnaces 560 for receiving the rack of castings, and which enclosure also supports a cooling system 576, such as a liquid spray cooling system or a forced air or gas cooling system. In one aspect the movable quench station 570 can be supported on a wheeled carriage which can be moved between the various furnaces on rails 578. As will be appreciated by one of skill in the art, the movement of the quenching station 570 can be synchronized with the heat treatment cycles taking place in each batch-type furnaces 560 so that the quench station is prepared to received the treated castings as soon each batch of castings reaches the end of its second heating stage 530.

[0095] With the batch-type heat treating furnaces 560 of the solution heat treating system 550 of FIG. 17, the first transition 429 between the first heating stage 420 and the second heating stage 430 (FIG. 12) can be a “virtual” transition comprising an increase in the rate of heating the castings from a first heating rate 422 in the first heating stage to an initial or second heating rate 432 in the second heating stage 430. In one aspect the increase in the rate of heating can be achieved through an increased heat output from the primary heater assembly 566, such as with in increase in the speed of the variable frequency motor drive 567, or by the temporary activation of the one or more additional secondary heaters 568, as described above.

[0096] Despite the possible inefficiencies of batch-type heat treating resulting from the repeated heat cycling within the furnace chamber, one advantage provided by the heat treating furnaces 560 of FIG. 17 is that the time duration (t_1) 424 of the first heating stage 420 can be defined by the first heating rate 422, while the time duration (t_2) 433 of the second heating stage 430 can be defined by the opening of the access door 564 and removal of the castings 505 from the furnace enclosure 562.

[0097] Additional detail and information regarding the thermal treatment systems disclosed above can also be found in aforementioned U.S. Provisional Patent Application No. 62/153,724, as referenced and incorporated above.

[0098] In applying the second and different thermal treatment protocol to the second test casting, the same support fixture and support profile can be used to carry the casting within the thermal treatment zones, so as to reduce the number of variables that could affect the results of the second test. Once the second thermal treatment protocol is complete, the second treated casting 101 can also be allowed to cool until a state of thermal equilibrium at the predetermined measurement temperature is reach, at which point another digitized, three dimensional surface measurement of the second casting 101 can

be captured to determine its post-treatment three dimensional shape. This can be followed by a comparison of the post-treatment shape of the second casting with its baseline shape, similar to that shown in FIGS. 13-14, to determine a reduction in or even the absence of the previously-identified dimensional distortion, and thereby verify that part or all of the previous distortion was due to high gas content in the alloy material.

[0099] It will be appreciated that a positive indication of high gas content within the HPDC castings, especially if the distortion and dissolved gases are localized within a specific region of the casting, can be useful information for the manufacturer or designer of the HPDC dies. With this information the die manufacturer may be able to redesign the die or HPDC process in such a way so as to reduce the amount of gases that are available for absorption by the molten casting material. For example, in one aspect the vents in the mold cavity could be modified or relocated to provide a better escape path for the gases and vapors that are present within the mold cavity when the hot melt is introduced at high pressure and velocity. In other aspects the gates for directing the molten metal into the mold cavity could also be modified or repositioned to better control the flow pattern as the casting material fills cavity and pushes the gases and vapors out through the vents.

[00100] With reference back to FIGS. 4 and 13-14, if it is determined that the dimensional distortions 182, 184 in the treated test casting 101 are the result of inadequate support providing by the support profile of the first support fixture 140, the relative positions of the support plates 142 and/or the shapes of their top edges can be modified to adjust the contact locations between the open support surface (i.e. support profile) of the second or modified support fixture and the underside or side edges of the casting 101. For instance, if a distortion is identified as being caused by sagging, the support fixture 140 can then be modified to include an additional contact location between the top edge of the support plate and the casting 101 to better support the affected portion during production runs. This could be accomplished by relocating a support plate or adding a new support plate underneath the affected portion, and/or by reshaping the top edge of a support plate that was already located beneath the affected portion.

[00101] The initial or first thermal treatment protocol can then be re-applied to the second casting supported on the second fixture so as to reduce the number of variables that could affect the results of the second test. Once the second run through the first thermal treatment protocol is complete, the second casting can also be allowed to cool until a state of thermal equilibrium at the predetermined measurement temperature is reached, at which point another digitized, three dimensional surface measurement of the treated second casting 101 can be captured to determine its post-treatment three dimensional shape. This can be followed by a comparison of the post-treatment shape of the second casting with its baseline shape, similar to that shown in FIGS. 13-14, to determine a reduction in or even the absence of the previously-identified dimensional distortion, and thereby verify that part or all

of the distortion is due to due to the inadequate support provided by the first support fixture. At this point the support fixtures for the high volume production runs can then be manufactured with the second support profile.

[00102] As discussed above, it is also possible for the dimensional distortions 182, 184 in the treated test casting 101 to be the result of an incomplete or improper application of thermal fluids to the casting within the thermal treatment zones, and particularly in a manner that creates large temperature gradients through the thickness or across the expanse of the alloy material resulting in dimensional distortions that remain set within the casting material after the thermal treatments are completed and the casting has returned to an ambient equilibrium temperature. Moreover, the improper application of thermal fluids is generally more of an issue during the quench stage 440 of the thermal treatment protocol 400 (FIG. 12). This is because the cooling rate 442 during quenching is so much greater than the heating rates 422, 432 during the heating stages, which makes it difficult to maintain the relative temperatures of the various portions of the casting substantially equal to each other during the rapid transition from the final casting temperature 435 to the quench temperature 445. It has been determined by the inventors that improvements in the thermal treatment of castings to reduce dimensional distortions can be accomplished through control or modification of the type and direction of thermal fluids that are applied to the casting, the position and orientation of the casting relative to the flow of thermal fluids, or both.

[00103] For example, in another aspect of the present disclosure shown in FIG. 18, the quench stage 440 can be performed by a multi-stage quench system 600 that generally includes a housing 620 comprising an enclosure 622 that surrounds a quench chamber 626 within which the one or more hot castings (represented in the drawings as a single test casting 100) can be positioned using the same support system 110 that supports the casting during the heat treating stages of the thermal protocol 400. As described above, the support system 110 can include the support fixture 140 that extends upward from the tray 120 to contact the casting at a few locations across its underside surface and/or lower edges so as to loosely maintain the casting at a desired position and orientation within the quench chamber 626, but with both the support fixture 104 and tray 120 otherwise being largely open or empty so to not block the flows of the various cooling fluids from reaching the casting.

[00104] The multi-stage quench system 600 also generally includes a pressurized liquid spray cooling system 630 and a bulk air cooling system 640. The liquid spray cooling system 630 can include a source of pressurized cooling liquid in fluid communication with a plurality of nozzles 632 with nozzle heads 634 through one or more manifolds 631. The nozzles 632 are configured to spray the cooling liquid 636 onto the hot casting 100 during one or more portions of the quench cycle to provide a liquid spray quench. The cooling liquid 636 can generally comprise water or a mixture of water and one or more additional liquid components, such as glycol. In addition, the nozzle heads

634 can be configured to provide the cooling liquid 636 in a variety states, from high pressure/high velocity streams with large drops to atomized mists formed from droplets having an average size of less than or about 100 μm . In another aspect, the temperature of the cooling liquid 636 prior to dispersal from the nozzles may be maintained at a predetermined temperature that has been optimized to provide the desired cooling affects.

[00105] The nozzles 632 and nozzle heads 634 of the liquid spray cooling system 630 can be configurable in both direction and flow so as to provide precision control over the application of cooling liquid 636 onto the hot casting 100 for extracting heat therefrom. For example, the configuration of individual nozzles 632 and nozzle heads 634 may be customizable, either manually or by programmable actuation, to match a particular casting part, so as to increase the amount of cooling liquid 636 that is applied to the thicker portions of the test casting relative to the amount of cooling liquid that is applied to the thin-wall portions of the casting. Furthermore, the cooling liquid can be simultaneously applied to all sides or exposed surfaces of the casting (i.e. front, back, sides, bottom, top, or internally). In this way the casting may be cooled in a substantially uniform manner throughout the liquid spray cooling portion(s) of the quenching cycle. Because the relative temperatures of the various portions of the casting can be maintained substantially equal throughout the quenching cycle, any thermally-induced internal stresses and the resulting dimension distortions of the casting can be substantially reduced.

[00106] The bulk air cooling system 640 can include one or more rotatable cooling fans 642 that are configured to provide a bulk flow of cooling air 644 that enters the quench chamber 626 through an entrance 624, passes across and around exterior surfaces of the hot casting 100 to remove heat from the casting, and then exits the chamber 626 through one or more exits 628 as an exhaust flow 648. In one aspect the temperature and flow rate of the bulk cooling air 644 can be controlled to provide the desired cooling characteristics. For instance, the motors driving the rotatable cooling fans 642 can be powered by variable frequency drives (VFDs) that can provide a continuously variable bulk flow of cooling air across a wide range of operating speeds or frequencies. The bulk air cooling system 640 and the chamber 626 may also be configured to ensure that the cooling air 644 passes over substantially all of the exposed exterior surfaces of the casting to cool the casting in a substantially uniform manner throughout the force air cooling portion(s) of the quenching cycle.

[00107] As understood by one of skill in the art, moreover, the configuration of the bulk air cooling system 640 depicted in FIG. 18 is merely illustrative of a generalized bulk air system that provides a stream of cooling air 644 that surrounds the casting 100. This is because the cooling fan 642 could be positioned above or below the chamber 626 or even remote from the chamber, and configured to draw or push the cooling air through the chamber and across the casting from any direction. Indeed, as the heated exhaust air 648 could at times be mixed with steam from the liquid spray cooling system 630,

it may be advantageous to draw the cooling air 644 into the chamber from below and discharge the mixed exhaust air 648 and heated water vapor through exits located in the upper portion of the chamber 626, in a direction opposite from that illustrated in FIG. 18.

[00108] The multi-stage quench system 600 also generally includes a programmable controller 616, such as a computer or similar electronic processor-based device, that is configured to activate and deactivate the bulk air cooling system 40 and the pressurized liquid spray cooling system 630. Thus, the controller 616 can be used to adjust the cooling provided by the liquid spray cooling system 630 and the bulk air cooling system 640 to ensure that each type of casting 100 can experience a specific, pre-programmed quenching process. In one aspect the controller 616 can also be used to automatically adjust the positioning and flow of liquid through individual nozzles 32, as described above. Alternatively, the quench system 600 may utilize a basic timer system wherein a set defined time schedule is used for sequentially activating and deactivating each of the cooling systems 630, 640.

[00109] Also shown in FIG. 18 is an optional temperature sensing system 610 that can measure and monitor the surface temperature of the casting 100 through the use of one or more temperature sensors 612. In one aspect the temperature sensors 612 can remotely measure the surface temperature of the casting at one or more locations without contacting the surface, such as with an infrared sensor. In other aspects the one or more temperature sensors may be located directly on or within the casting part. Electrical communication can be established between the temperature sensors 612 and the programmable controller 616 through control wiring 614, with the programmable controller 616 being used to monitor and record the reduction in the surface temperature of the casting as it undergoes the quenching process.

[00110] Once the hot casting 100 has been positioned or secured within the quench chamber 626, the bulk air cooling system 640 and the liquid spray cooling system 630 can be operated independently, or together, to rapidly quench the casting using a predetermined sequence of quenching stages or steps. For example, one exemplary embodiment of utilizing the multi-stage quench system 600 of the present disclosure is expressed below, as might be applied to an aluminum alloy casting. In particular, the temperature vs. time graph of a representative process 650 for quenching the aluminum alloy casting is provided in FIG. 19 (also known as a quench profile), in which the temperature 652 of the casting can be quickly and uniformly reduced in three or more distinct stages or phases that include alternating operation of the bulk air cooling system 640 and the liquid spray cooling system 630. As discussed above, this rapid yet controlled reduction of the temperature 652 of the casting in a substantially uniform fashion can result in a high strength part with minimal dimensional distortions.

[00111] Prior to entering the first stage (“Stage I”) 660 of the quenching process 650, the hot casting can be placed into the quench system at an initial temperature 662, such as an elevated post heat treatment temperature as the casting leaves a solution furnace. The bulk air cooling system 640 can then be activated to provide a Stage I air quench 664 that cools the casting from the initial temperature 662 to a first intermediate temperature 672. The Stage I air quench 664 takes place during a Stage I time period 666 that, in one embodiment, can last between about 5 seconds and about 20 seconds. In some aspects the Stage I cooling rate 668 can be substantially linear or constant (as also shown in FIG. 19), while in other aspects the Stage I cooling rate 668 may be non-linear or variable.

[00112] At the conclusion of the first stage 660 of the quenching process 600, the bulk air cooling system 640 can be deactivated and the liquid spray cooling system 630 activated to provide a second stage (“Stage II”) liquid (or liquid/air) spray quench 674 that further cools the casting from the first intermediate temperature 672 to a second intermediate temperature 682. The Stage II spray quench 674 can have a time period 676 that, in one embodiment, can last between about 5 seconds and about 20 seconds. In some aspects the Stage II cooling rate 678 can be substantially constant, while in other aspects the Stage II cooling rate 678 may be variable.

[00113] After the casting temperature has reached the second intermediate temperature 682, the liquid spray cooling system 630 can be deactivated and the bulk air cooling system 640 re-activated to provide a third stage (“Stage III”) air quench 684 that further cools the casting from the second intermediate temperature 682 to a final quench temperature 692. The Stage III spray quench 684 can have a time period 686 that, in one embodiment, lasts between about 5 seconds and about 10 seconds. In some aspects the Stage III cooling rate 688 can be substantially constant, while in other aspects the Stage III cooling rate 688 may be variable. When the Stage II cooling liquid is water, the Stage III air quench can also function to dry any residual moisture that remains on the casting after the Stage II spray quench 674. After reaching the final quench temperature 692, the casting can be allowed to gradually cool 144 to ambient temperature for natural aging, or may be transferred to a secondary furnace for artificial aging at an elevated temperature, and for an extended period of time, before being allowed to cool naturally.

[00114] As discussed above, each of the air quench stages 664, 684 and the spray quench stage 674 can be configured to cool the casting in a substantially uniform manner throughout the quench steps to reduce the thermally-induced stresses that may develop within the part. This feature of the disclosure can function to minimize or substantially reduce the thermally-induced dimensional distortions that may otherwise be generated during the quenching processes, resulting in fewer castings that are rejected for falling outside of dimensional tolerances.

[00115] In one embodiment the total time to perform the multi-stage quenching process 650 on a hot aluminum alloy casting, from the initial temperature 662 to the final quench temperature 692, can range from about 15 seconds to about 50 seconds. Although the multi-stage quenching process 650 can take longer than an immediate immersion quench in water or oil, as presently available in the art, the ability to variably control the cooling rate of the casting throughout the quenching process can result in a quenched casting with improved metallurgical properties and reduced dimensional distortions. In some aspects, moreover, it is contemplated that the multi-stage quenching process 650, when used to conclude a properly-optimized solution heat treatment process, can provide the resulting casting with such improved metallurgical properties that the additional step of artificially aging the casting at an elevated temperature in a secondary furnace may not be necessary to meet structural performance requirements.

[00116] It will be appreciated that the multi-stage quench system 600 and quenching process 1650 illustrated in FIGS. 18-19 is a batch-based or cell-based quench system in which each stage in the quenching process is performed at the same location on a casting that can be substantially fixed in space, or at least within the chamber 626 of the enclosure 620. However, it is also possible or even likely that mass produced castings will undergo the multi-stage quenching process 650 while moving through a continuous process quench system such as, for example, the quench system 700 illustrated in FIG. 20.

[00117] The multi-stage quench system 700 generally includes an elongated enclosure 202 that defines a quench chamber 206, with multiple castings (not shown) traveling through the chamber 706 at a substantially constant speed 701 from an entrance opening 704 at one end of the enclosure 702 to an exit opening 708 at the opposite end. The enclosure 702 can include a first section 710 having a bulk air cooling system 712 that provides a Stage I air quench 664 (FIG. 19). Depending on the speed 701 at which the castings travel through the enclosure 702, the first bulk air cooling system 712 may include one or more cooling fans 714 that provide a bulk flow of cooling air through the chamber 706. In one aspect the cooling fans 714 can be provided with VFD drives so that bulk flow of cooling air is continuously variable across a wide range of operating speeds, so that the rate of cooling provided within the Stage I air quench 664 of the quench system 700 can be adjustable to accommodate various types of castings with different quenching profiles.

[00118] After passing through the first section 710, the castings can then enter a second section 720 having a liquid spray cooling system 722 that provides a Stage II spray quench 674 (FIG. 19). The liquid spray cooling system 722 can include rows of nozzles 724 with nozzle heads 726 that spray a cooling liquid, such as water or a water/glycol mixture, onto the hot castings during the intermediate Stage II portion of the quenching process.

[00119] Upon reaching the end of the second section 720, the castings can then pass into a third section 730 having another bulk air cooling system 732 that provides the Stage III air quench 684 (FIG. 19). As with the first bulk air cooling system 712 proximate the entrance of the enclosure 702, the second bulk air cooling system 732 can also include one or more cooling fans 734, depending on the speed 701 at which the castings travel through the enclosure 702. The cooling fans 734 in the third section 730 of the quench system 700 can also be provided with VFD drives so that the rate of cooling provided within the Stage III air quench 734 may be adjustable.

[00120] Also shown in FIG. 20, the multi-stage quench system 700 can also include an optional temperature sensing system 760 that can measure the surface temperature of the castings through the use of a plurality of temperature sensors 762 that can be spaced along the length of the enclosure 702. In other aspects the one or more temperature sensors may be located directly on or within the casting part. Although not shown, it is understood that the temperature sensing system 760 can be in electrical communication with the programmable controller described above, which may be used to monitor, control, and record the reduction in the surface temperature of the castings as they pass through the quench system 700.

[00121] With continued reference back to FIGS. 4 and 13-14, if it is determined that the dimensional distortions 182, 184 in the treated test casting 101 are the result of an incomplete or improper application of thermal fluids to the casting within the thermal treatment zones, in one aspect the multi-stage quench systems 600, 700 disclosed in FIGS. 18-20 can be used to control the type and direction of thermal fluids that are applied to the casting during the quench stage to reduce thermal gradients and rapidly cool the casting in a substantially uniform manner. This multi-stage quenching approach can be especially effective when combined with the support system 110 and support fixtures 140 that can support the casting in space within the quenching chamber while otherwise being largely open or empty so to not block the flows of the various cooling fluids from reaching the casting.

[00122] Additional detail and information regarding these multi-stage quench systems can be found in co-owned and co-pending U.S. Patent Application No. 14/855,498, filed September 16, 2015, and entitled SYSTEM AND METHOD FOR QUENCHING CASTINGS, which application is incorporated by reference in its entirety herein.

[00123] Alternatively, in yet another aspect of the present disclosure shown in FIG. 21, the quench stage of the thermal protocol may be performed by a single-stage forced air quench system 800 for cooling castings 880 that generally includes a quench housing 820 and with at least one roller conveyor system 830 having a plurality of support rollers 832 extending across a center portion 822 of the quench housing 820. Forced air fans (not shown) can be located within a lower portion of the quench housing 820 for providing a stream of cooling air 890 that flows upward through the housing

to exit through one or more opening (also not shown) in the upper portion of the quench housing. The roller conveyor system 830 is configured to move one or more casting trays 860 loaded with castings 880 into the center portion 822 of the quench housing 820 where it will encounter the cooling air 890 provided by the forced air fans.

[00124] The quench air system 800 can also include a plurality of nozzle baffles 840 that extend inward from sidewalls 824 of the quench housing to 820 to the inside of the outermost rollers 832 of a roller conveyor. The nozzle baffles 840 can operate to redirect those portions 892 of the cooling air 890 that flow upward along the sidewalls 824 of the quench housing 820 toward the center portion of the quench housing 820, thereby increasing the speed of the forced cooling air 890 as it flows upward through the casting tray 860. In one aspect the nozzle baffles 840 can include fixed upwardly and inwardly slopped portions 842 that curve aerodynamically into vertical lips 846 that extend upward and adjacent to the inner edges of the outermost rollers 842, without contacting the rollers, so as to maximize the increase the velocity of the cooling air 890 while minimizing pressure losses. However, other configurations and/or shapes for the nozzle baffles 840 are possible and considered to fall within the scope of the present disclosure.

[00125] Although not shown in the schematic side view of FIG. 21, it is to be appreciated that similar nozzle baffles can also extend inward from the sidewalls of the quench enclosure 820 that are perpendicular to the sidewalls 824 shown in the drawing (i.e. into or out of the paper of the drawing). In this case the nozzle baffles can include notches or cutouts that fit around the rollers 832. Thus, in some aspects the nozzle baffles 840 can redirect and focus the forced cooling air 890 into an area that substantially corresponds to the footprint of the portion of the casting tray 860 that supports the castings 880, and which will generally be much smaller than the total cross-section area of the quench closure 820. Thus, the nozzle baffles 840 can provide a first redirection or concentration of the forced air flow and a corresponding first stage increase in the flow rate or velocity of the cooling air 890.

[00126] Also illustrated in FIG. 21, in some embodiments the air quench system 800 can further include a plurality of movable central baffles 850 that are located in the gaps 834 between support rollers 832 in the center portion 822 of the quench enclosure 820. Although viewed from their ends in the drawing, it is to be appreciated that the central baffles 850 can be elongate, vane-shaped structures that can substantially span the length of the support rollers. In addition, the central baffles 850 can be supported, either at their ends or at one or more mid-span locations, with an actuated support system that can move or rotate the central baffles 850 from the substantially horizontal orientation shown in FIG. 21 to a substantially vertical orientation, as well as any desired angular orientation therebetween. When moved into a horizontal or angled orientation, the central baffles can function to further redirect and concentrate the upwardly-flowing forced cooling air into narrow gaps or channels 836 between the central baffles 850 and the outer circumferential surfaces of the support rollers 832, thereby

further increasing the velocity of the cooling air 890 into predetermined channels as it flows around and through the castings 880. This second and more localized redirection or concentration of the forced air flow can comprise a second stage increase in the flow velocity, leading to a corresponding increase in the rate at which heat is collected and drawn away from the heated casting metal.

[00127] Although not visible the drawing, in one aspect the width of the central baffles 850 may vary along the length of the vane-shaped structure (i.e. while moving perpendicular to the plane of the drawing) so as to define channels of varying size and shape that can be optimized to better define and shape the streams of cooling air 890. For example, in some aspects the profile of the central baffles 850 can be shaped to match large openings 882 formed through the castings 880 themselves (for example, empty cylinder bores or crank shaft bores), so that a high velocity stream of cooling air can be directed to flow upward through the interior of the castings in addition to the high velocity streams of cooling air flowing across the exterior surfaces of the castings 880. In this way a greater proportion of the cooling air provided by the forced air fans can be utilized to cool the castings, thereby increasing the effectiveness, efficiency and cooling rates of the quench system 800.

[00128] FIG. 22 is a schematic side view of another representative embodiment of the single-stage forced air quench system 900 for cooling castings 980 that includes two roller conveyor systems 930, 935, with a second or upper roller conveyor 935 positioned directly above the first or lower roller conveyor 930 in the center portion 922 of the quench enclosure 920. However, in this embodiment the forced air fans (not shown) can be located above the quench stations, so that the stream of cooling air 990 provided by the fans flows downward through both roller conveyor systems 930, 935. In this embodiment the second roller conveyor 935 can be useful for minimizing the switch out time between a first casting tray 960 loaded with a first group of castings 980 and a second casting tray loaded with a second group of castings, as the upper casting tray 966 can be moved into position on the upper quench station without interfering with the simultaneous withdrawal of the lower casting tray 960 from the lower quench station.

[00129] Both quench stations in the quench air system 900 can include nozzle baffles 940, 946 and movable central baffles 950, 956. The nozzle baffles 940, 946 can be fixed, and can serve to redirect those portions 992 of the cooling air 990 that flow downward along the sidewalls 924 toward the center portion 922 of the quench housing 920, thereby focusing and increasing the speed of the forced cooling air 990 as it flows downward through and around the castings that are supported on the casting trays. In this embodiment, however, the nozzle baffles 940, 946 can extend inward from the sidewalls 924 at locations above the roller conveyors 930, 935 of each quench station and by a distance 926 that allows a casting tray loaded with castings to roll in under the nozzle baffles, which in one aspect can include the lower vertical lips 944, 948 shown in the illustrated embodiment. In addition, since the nozzle baffles are located above the quench stations, the size and shape of the

nozzle baffles 940, 946 is not constrained by the roller conveyers. This can allow the nozzle baffles to be configured or customized, if so desired, to more accurately conform to the footprint of the castings 980 that are loaded on their respective casting trays 960. As these flow areas will generally be much smaller than the total cross-sectional area of the quench closure 920, the nozzle baffles 940, 946 can provide a first redirection or concentration of the forced air flow and a corresponding first stage increase in flow velocity.

[00130] Similar to the embodiment of the quench air system described above, the movable central baffles 950, 956 that are positioned near or within the mouth of the nozzle baffles 940, 946 can provide a second and more localized redirection or concentration of the forced air flow and a corresponding second stage increase in flow velocity. The central baffles 950, 956 can also be provided with shaped profiles that can define and shape the streams of cooling air to correspond with openings and/or other structures formed into the castings below, and in this way can be used to tailor the cooling stream to provide improved cooling for specific castings. However, since the movable central baffles 950, 956 are also located above the quench stations and not constrained by the roller conveyers 930, 935, the number, size and shape of the central baffles 950, 956 can be substantially different than those movable baffle designs that are intermixed with the rollers (see, for example, the embodiment of FIG. 21)

[00131] When the first casting tray 960 loaded with a first group of castings 980 is positioned within the lower quench station, the central baffles 950 that are associated with the first station can be moved or rotated to their active orientations (in the depicted case, a horizontal orientation) that redirects and concentrates the downwardly-flowing forced cooling air into narrow gaps or shaped channels 935 that correspond with openings or other structures formed into the castings 980 below. At the same time, the central baffles 956 that are associated with the second quench station (that is now upstream of the first quench station) can be moved to their vertical or inactive orientations so as to reduce any drag and pressure losses caused by the overlying structures.

[00132] When the first casting tray 960 is withdrawn from the lower quench station and the second casting tray loaded with a second group of castings is positioned within the upper quench station (not shown), it will be appreciated that the central baffles 950 that are associated with the first station can be moved to their vertical or inactive orientations so as to reduce the backpressure generated by the structures that are now downstream of the castings being quenched. At the same time, the central baffles 956 that are associated with the second quench station can be moved or rotated to their active orientations (e.g. a horizontal orientation) that redirects and concentrates the downwardly-flowing forced cooling air into narrow gaps or shaped channels 935 that correspond with the openings or other structures formed into the castings 986 immediately below.

[00133] Additional detail and information regarding these forced air quench can be found in co-owned and co-pending U.S. Provisional Patent Application No. 62/197,199, filed July 27, 2015, and entitled SYSTEM AND METHOD FOR IMPROVING QUENCH AIR FLOW, which application is incorporated by reference in its entirety herein.

[00134] In yet another aspect of the present disclosure illustrated FIG. 23, it is also possible perform a numerical analysis, such as thermal finite element analysis, on the casting 200, the casting support system 210, and the thermal treatment zone 290 (FIG. 6) during development of the thermal treatment protocol to determine the flow pattern 293 of thermal fluids, such as heated air or cooling air, around the casting 200 and the projected heat transfer rates across the surfaces of the casting. If it is determined that the heat transfer rates are improperly balanced between the thin wall portions 203 and thick wall portions 205 in a manner that would create temperature gradients through the thickness and/or across the expanse of the alloy material, then the support profile of the support fixture 240 could be modified to adjust the position and/or orientation of the casting 200 within the flow pattern 293, or to improve or re-direct the flow pattern to the underside the casting 206 using one or more deflectors. In this way the casting support system 210 can be used to facilitate uniform and evenly-applied thermal treatments that reduce the internal temperature gradients across the treated casting 200 as the overall temperature of the part is being raised or lowered.

[00135] In sum, the methods and systems of the present disclosure can be employed to improve the thermal treatment of castings, and in particular the thermal treatment of production HPDC castings, for enhanced metallurgical properties and reducing dimensional distortions. The methods and systems generally include the knowledgeable application of the customizable casting support system described above, in combination with thermal treatment systems that are capable of adjustably applying thermal treatment protocols to mitigate or avoid many of the problems associated with the high volume production of thin wall aluminum alloy castings that have been formed in an (HPDC) process

[00136] The invention has been described herein in terms of preferred embodiments and methodologies considered by the inventor to represent the best mode of carrying out the invention. It will be understood by the skilled artisan, however, that a wide range of additions, deletions, and modifications, both subtle and gross, may be made to the illustrated and exemplary embodiments without departing from the spirit and scope of the invention. These and other revisions might be made by those of skill in the art without departing from the spirit and scope of the invention that is constrained only by the following claims.

CLAIMS

1. A method for improving the thermal treatment of castings for enhanced metallurgical properties, the method comprising:

- obtaining a plurality of untreated castings of a given casting design;
- capturing three dimensional surface measurements of the castings to determine a baseline three dimensional shape for the castings;
- obtaining a first support fixture configured to support the castings, with a first support profile, within at least one thermal treatment zone;
- applying a thermal treatment protocol to a first casting supported on the first support fixture;
- capturing a three dimensional surface measurement of the first casting to determine its post-treatment three dimensional shape;
- comparing the baseline shape with the post-treatment shape of the first casting;
- identifying at least one dimensional distortion in the first casting resulting from inadequate support or positioning during the thermal treatment protocol;
- obtaining a second support fixture configured to support the castings, with a second support profile, that is different from the first support profile;
- applying the thermal treatment protocol to a second casting supported on the second support fixture;
- capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape;
- comparing the baseline shape with the post-treatment shape of the second casting; and
- identifying a reduction in a dimensional distortion to verify that the dimensional distortion is at least partially due to inadequate support or positioning during the thermal treatment protocol.

2. The method of claim 1, wherein the first and second support fixtures further comprise an open lattice having a plurality of top edges that together define the first and second support profiles, respectively, that are substantially complementary with an underside surface of the castings and configured to loosely support the castings atop the lattice and orientate the castings in space above the first support fixture.

3. The method of claim 2, wherein the first and second support profiles further comprise a plurality of discrete contact locations separated by gaps where the top edges are spaced from the underside surface of the castings.

4. The method of claim 3, wherein the plurality of discrete contact points of the second support profile are different than the plurality of discrete contact points of the first support profile.

5. The method of claim 1, wherein a position and orientation of the castings in the second support profile is different from the position and orientation of the castings in the first support profile.

6. The method of claim 5, wherein applying the thermal treatment protocol to the second casting further comprises altering a flow of thermal fluids directed toward a location of the at least one dimensional distortion.

7. The method of claim 6, wherein the flow of thermal fluids further comprises a cooling fluid in a quench process.

8. The method of claim 1, wherein the untreated castings are pre-production prototype castings.

9. The method of claim 1, further comprising comparing the three dimensional surface measurement for each of the untreated castings to identify inconsistencies in the casting process.

10. The method of claim 1, further comprising identifying at least one dimensional distortion resulting from high gas content in the alloy material of the first casting during the thermal treatment protocol.

11. The method of claim 10, wherein identifying the at least one dimensional distortion resulting from high gas content further comprises inspecting a surface of the first casting proximate the at least one dimensional distortion to identify surface porosity related to high gas content in the alloy material.

12. The method of claim 10, wherein identifying the at least one dimensional distortion resulting from high gas content further comprises sectioning the first casting proximate the at least one dimensional distortion to identify internal porosity related to high gas content in the alloy material.

13. The method of claim 10, further comprising:
applying an altered thermal treatment protocol to a third casting supported on the second support fixture;
capturing a three dimensional surface measurement of the third casting to determine its post-treatment three dimensional shape;
comparing the baseline shape with the post-treatment shape of the third casting; and
identifying a reduction in another dimensional distortion resulting to verify that the dimensional distortion is at least partially due to high gas content in the alloy material.

14. The method of claim 13, wherein applying the altered thermal treatment protocol further comprises reducing a period of time the casting experiences temperatures above a predetermined silicon solution temperature.

15. A method for optimizing the thermal treatment of castings for improved metallurgical properties, the method comprising:

obtaining a plurality of untreated castings of a given casting design;

capturing three dimensional surface measurements of the castings to determine a baseline three dimensional shape for the castings;

obtaining a support fixture including an open lattice having a plurality of top edges that together define an open support surface that is substantially complementary with an underside surface of the castings and configured to loosely support the castings atop the lattice and orientate the castings in space above the support fixture;

applying a thermal treatment protocol to a first casting supported on the support fixture;

capturing a three dimensional surface measurement of the first casting to determine its post-treatment three dimensional shape;

comparing the baseline shape with the post-treatment shape of the first casting; and

identifying a dimensional distortion in the first casting.

16. The method of claim 15, further comprising:

obtaining a second support fixture including an open lattice having a plurality of top edges that together define a second open support surface that is different from the open support surface of the first support fixture;

applying the thermal treatment protocol to a second casting supported on the second support fixture;

capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape;

comparing the baseline shape with the post-treatment shape of the second casting; and

identifying a reduction in the dimensional distortion in the second casting to verify that the dimensional distortion is at least partially due to inadequate support or positioning during the thermal treatment protocol.

17. The method of claim 16, wherein the first and second open support surfaces further comprise a plurality of discrete contact locations separated by gaps where the top edges are spaced from the underside surface of the castings, with the plurality of discrete contact points of the second open support surface being different than the plurality of discrete contact points of the first open support surface.

18. The method of claim 16, wherein a position and orientation of the castings on the second open support surface is different from the position and orientation of the castings in the first open support surface.

19. The method of claim 16, wherein applying the thermal treatment protocol to the second casting further comprises altering a flow of thermal fluids directed towards the location of the at least one dimensional distortion.

20. The method of claim 15, further comprising:
applying a second thermal treatment protocol to a second casting supported on the support fixture;
capturing a three dimensional surface measurement of the second casting to determine its post-treatment three dimensional shape;
comparing the baseline shape with the post-treatment shape of the second casting; and
identifying a reduction in the dimensional distortion in the second casting to verify that the dimensional distortion is at least partially due high gas content in the alloy material.

21. The method of claim 20, wherein applying the second thermal treatment protocol further comprises reducing a period of time the second casting experiences at temperatures above a predetermined silicon solution temperature of the alloy material.

22. A method for improving the thermal treatment of castings for enhanced metallurgical properties, the method comprising:

obtaining a plurality of untreated castings of a given casting design;
capturing three dimensional surface measurements of the castings to determine a baseline three dimensional shape for the castings;
obtaining a first support fixture configured to support the castings, with a first support profile, within at least one thermal treatment zone;
applying a thermal treatment protocol to a first casting supported on the first support fixture;
capturing a three dimensional surface measurement of the first casting to determine its post-treatment three dimensional shape;
comparing the baseline shape with the post-treatment shape of the first casting;
identifying at least one dimensional distortion in the first casting .

FIG. 1
PRIOR ART

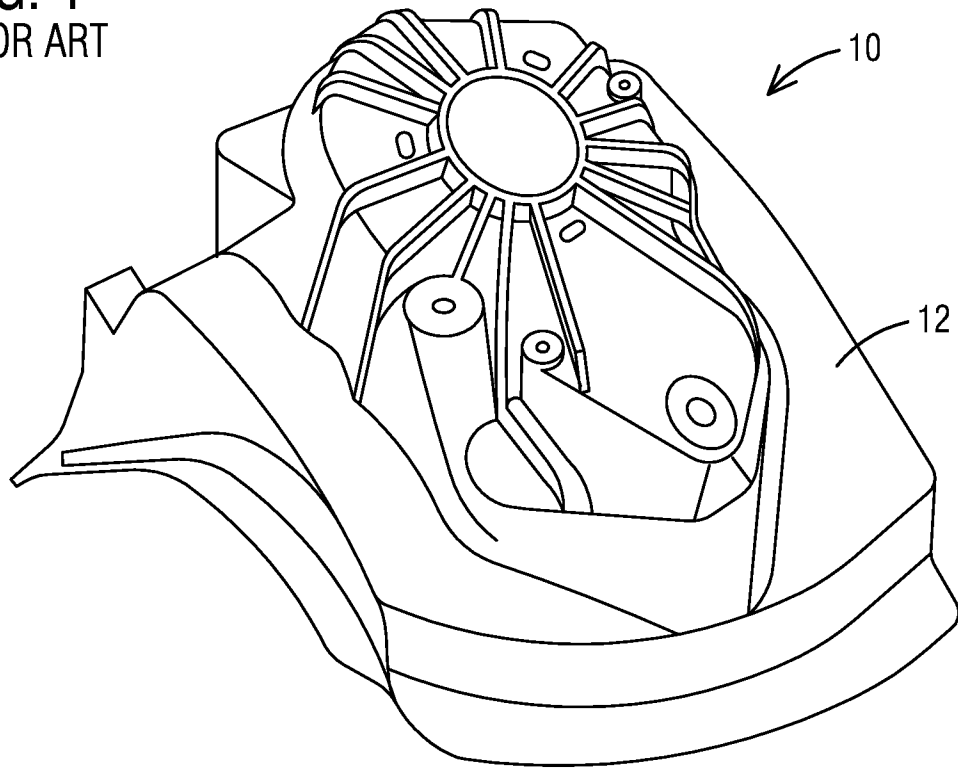
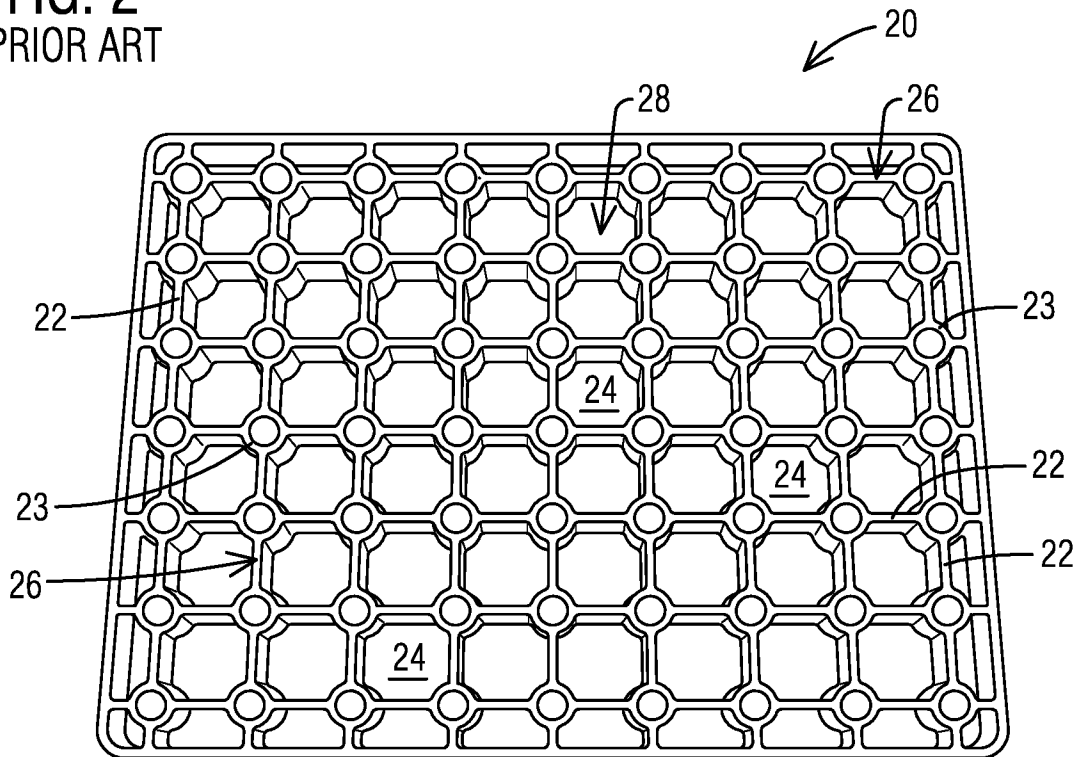


FIG. 2
PRIOR ART



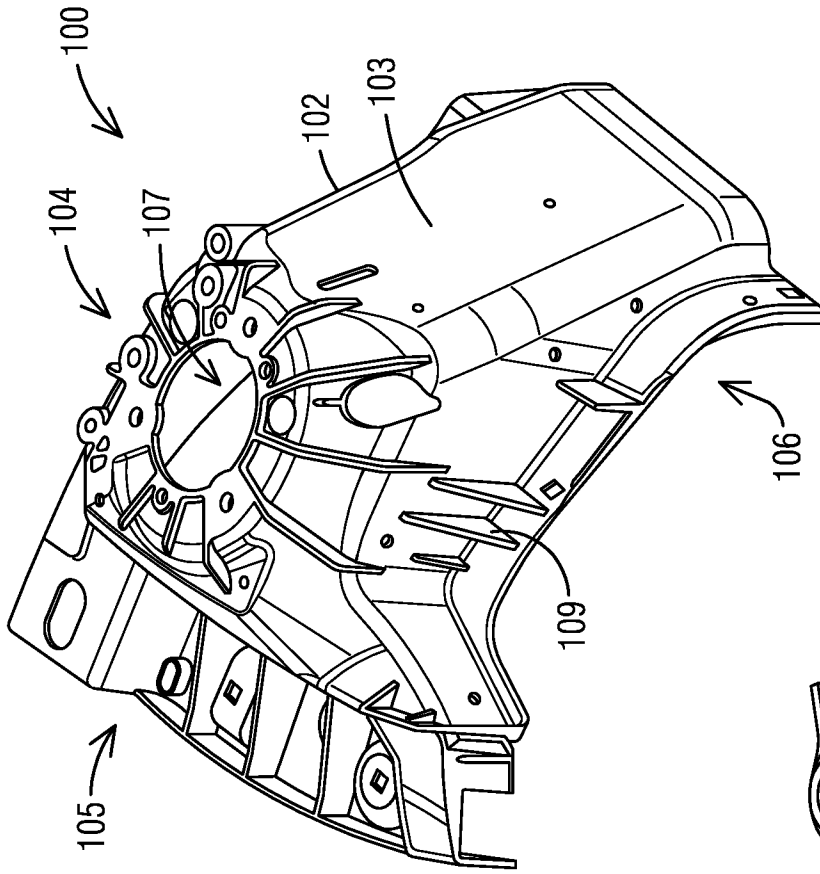


FIG. 3

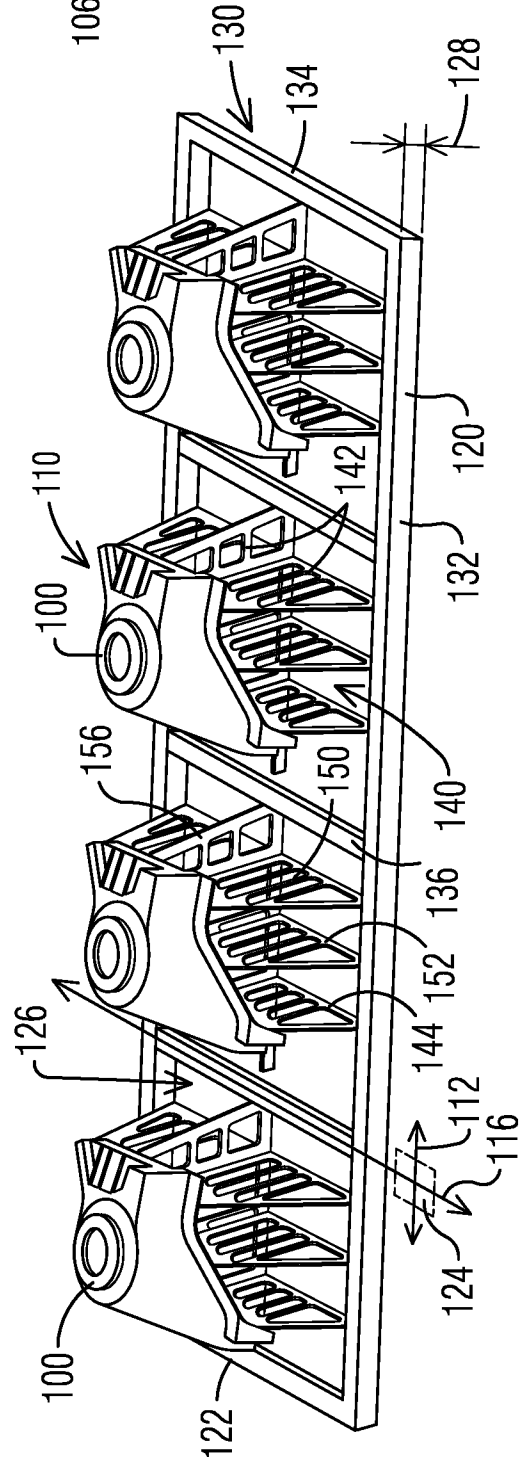


FIG. 4

FIG. 5

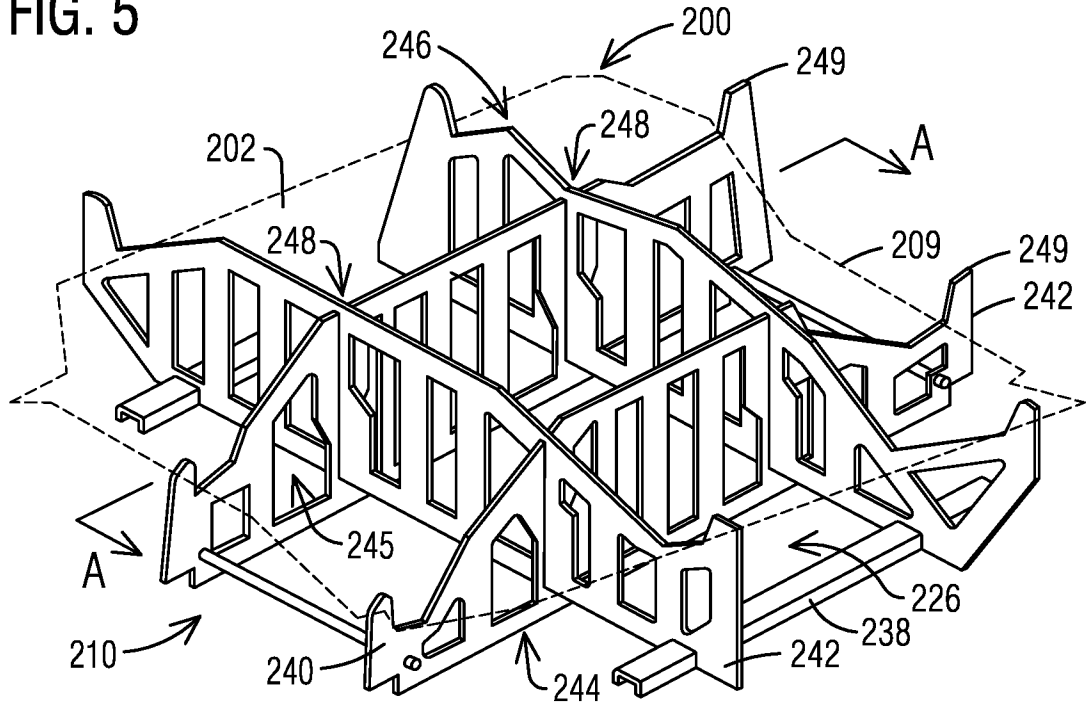


FIG. 6

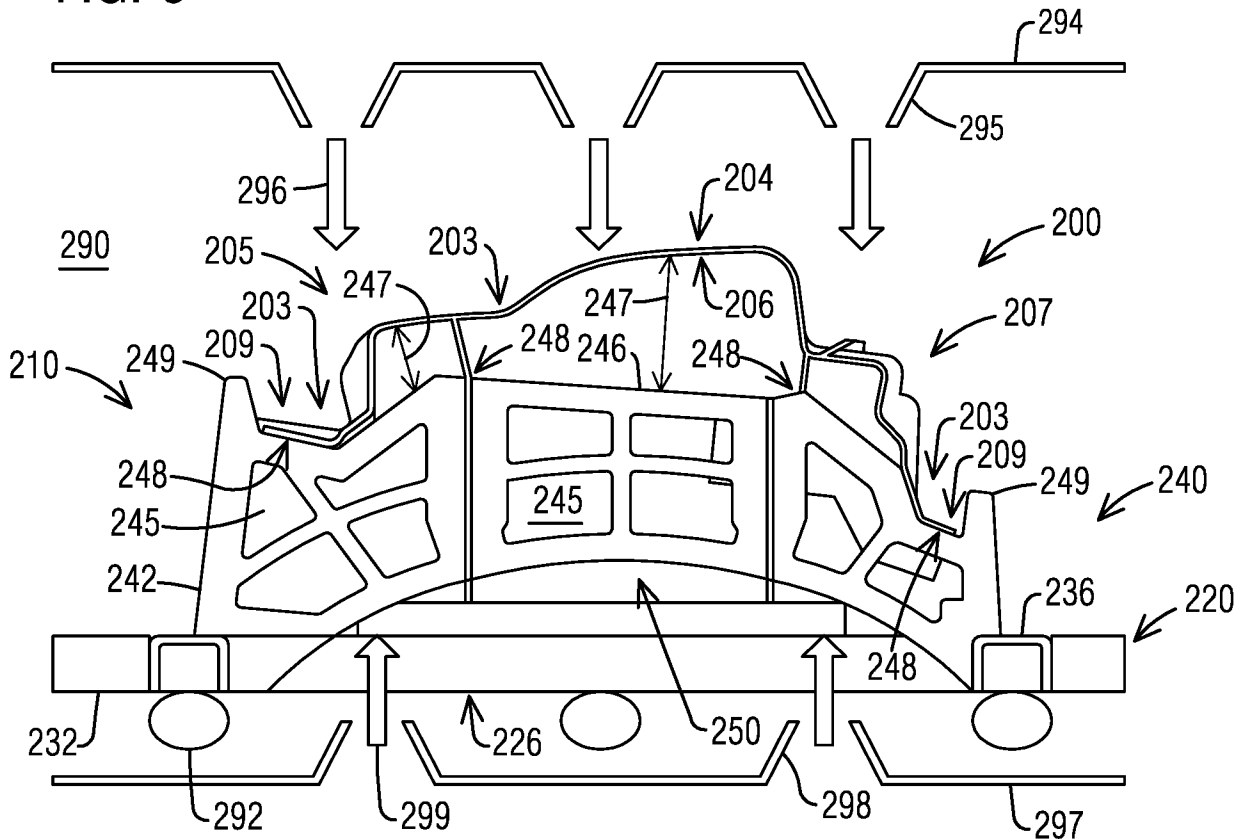


FIG. 7

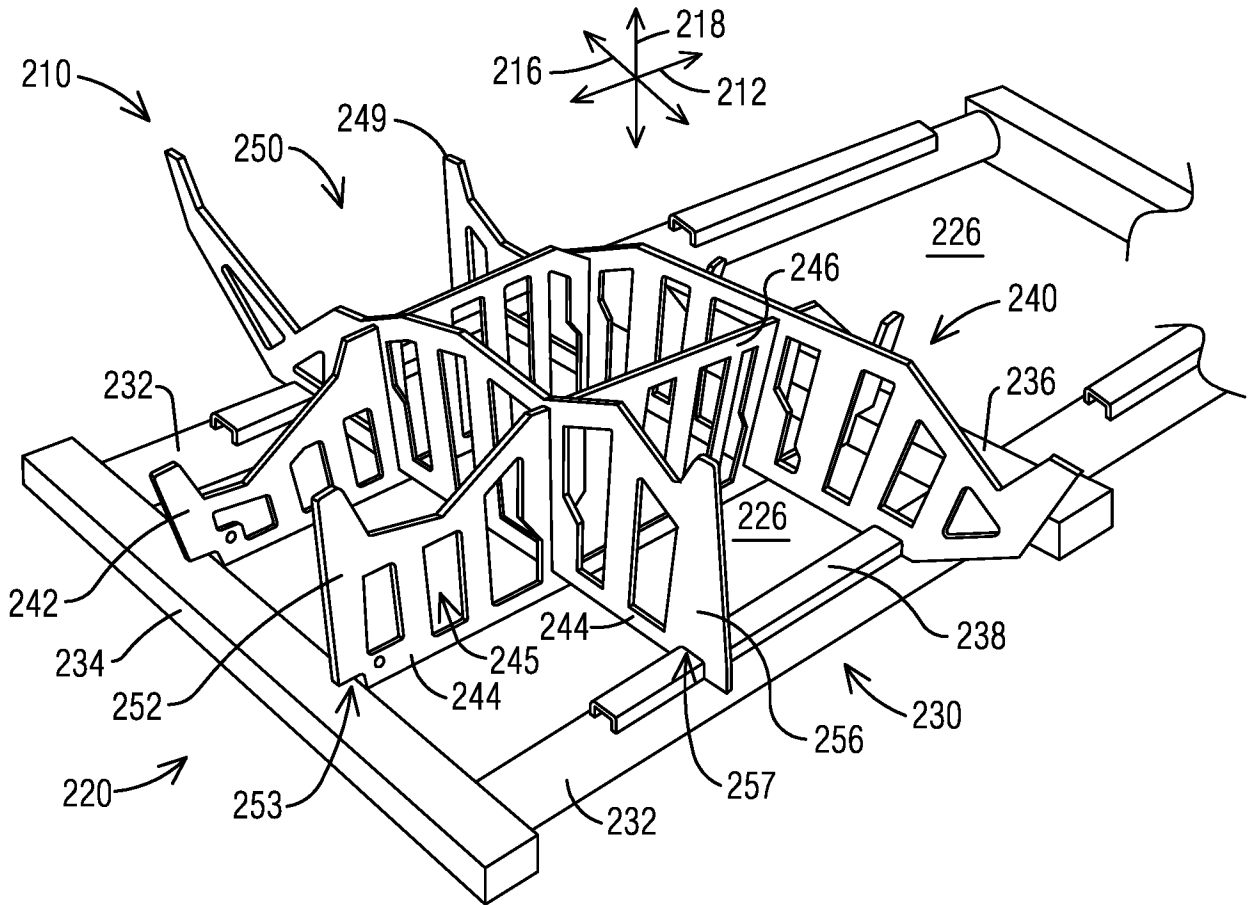
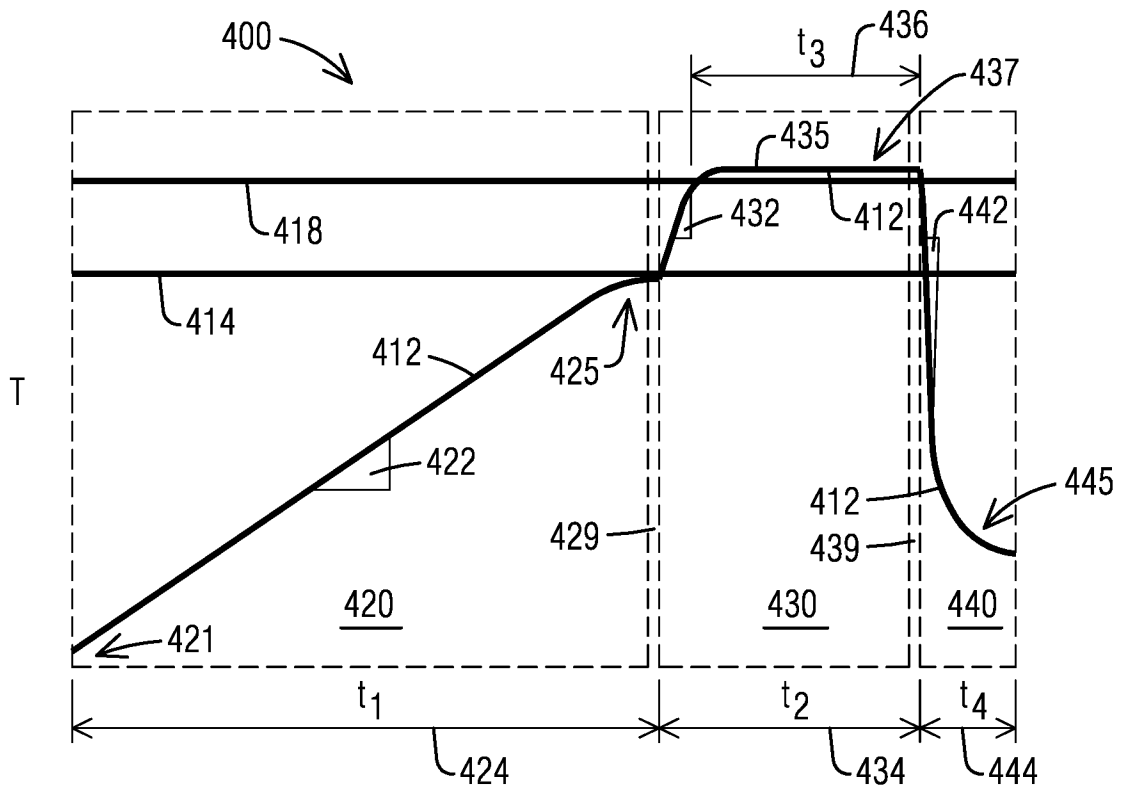


FIG. 12



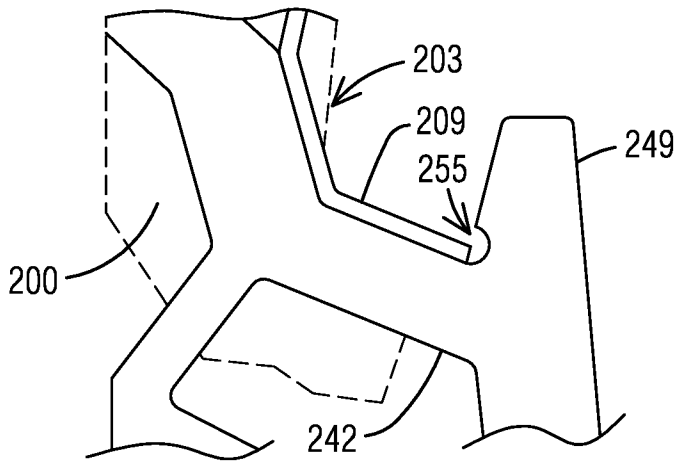


FIG. 9

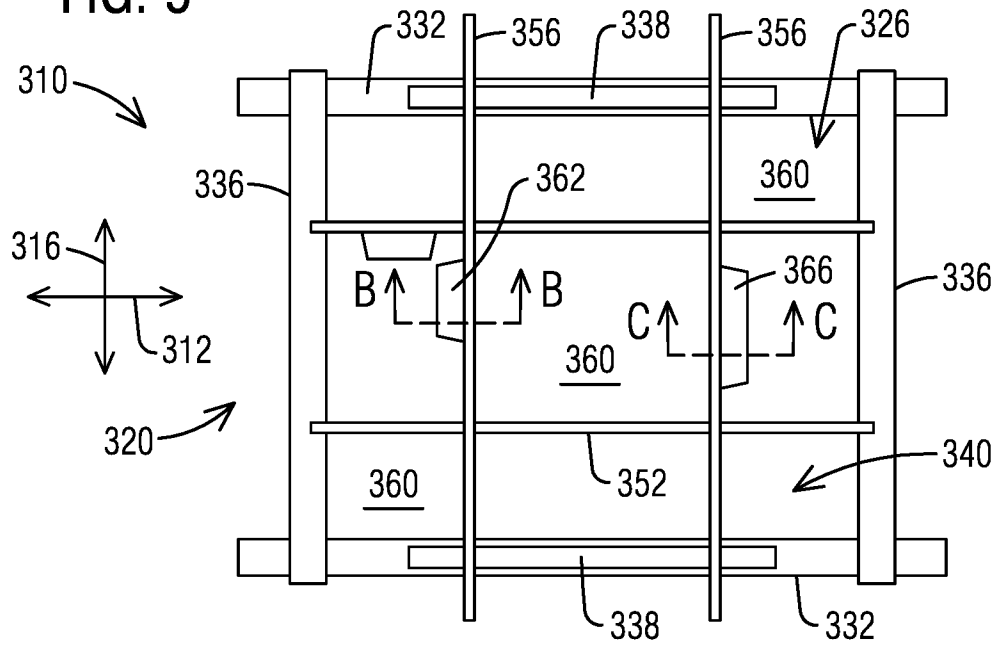


FIG. 10

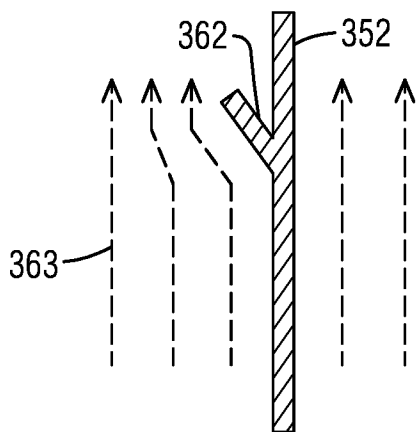


FIG. 11

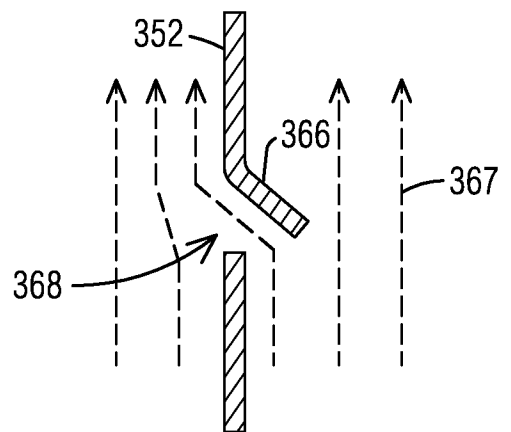


FIG. 13

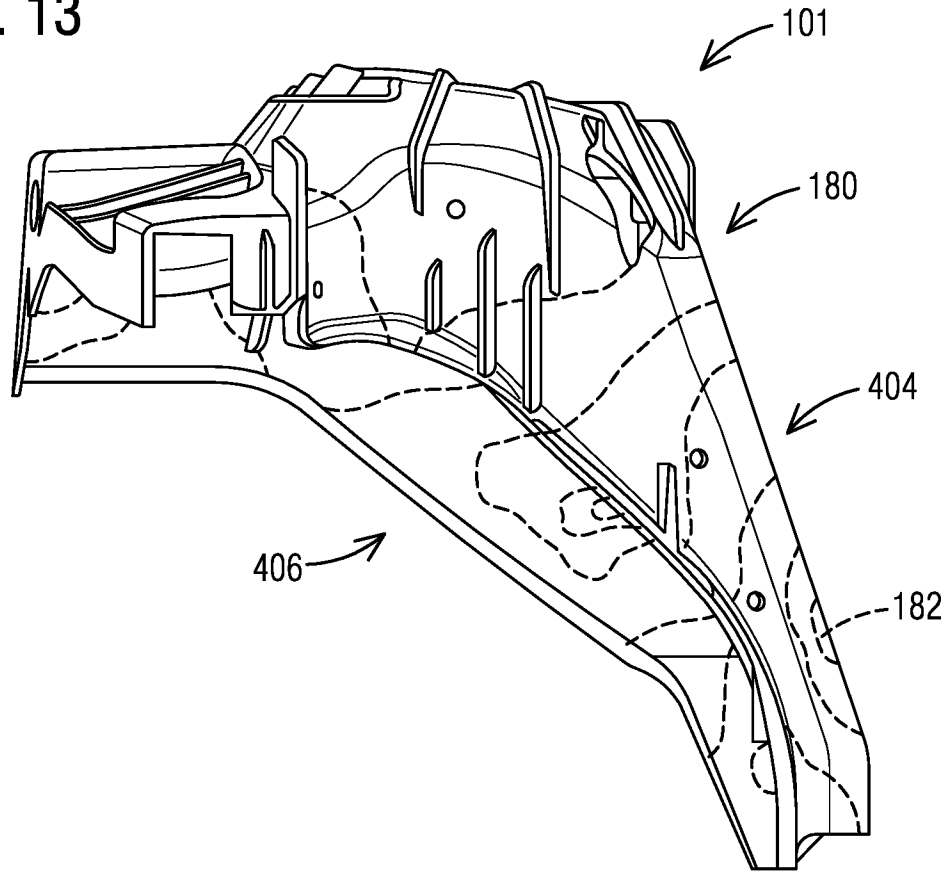


FIG. 14

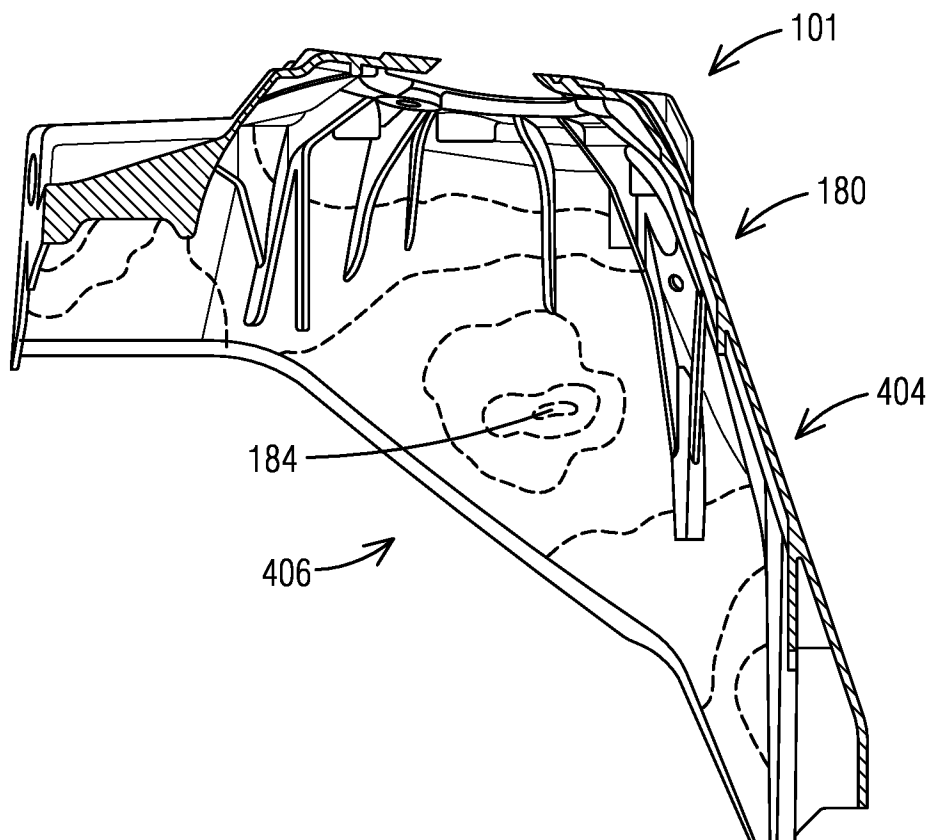


FIG. 17

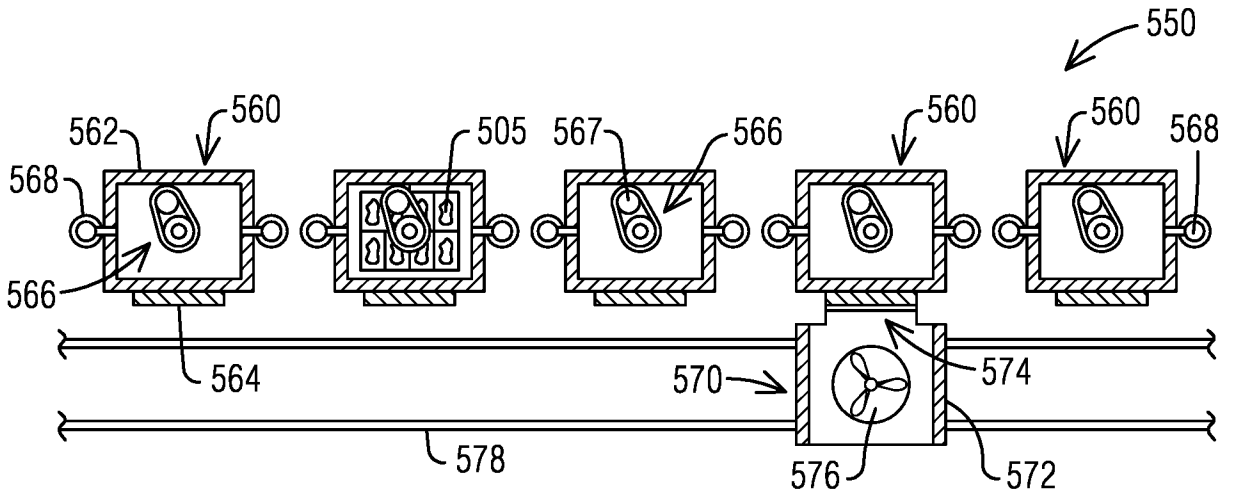


FIG. 18

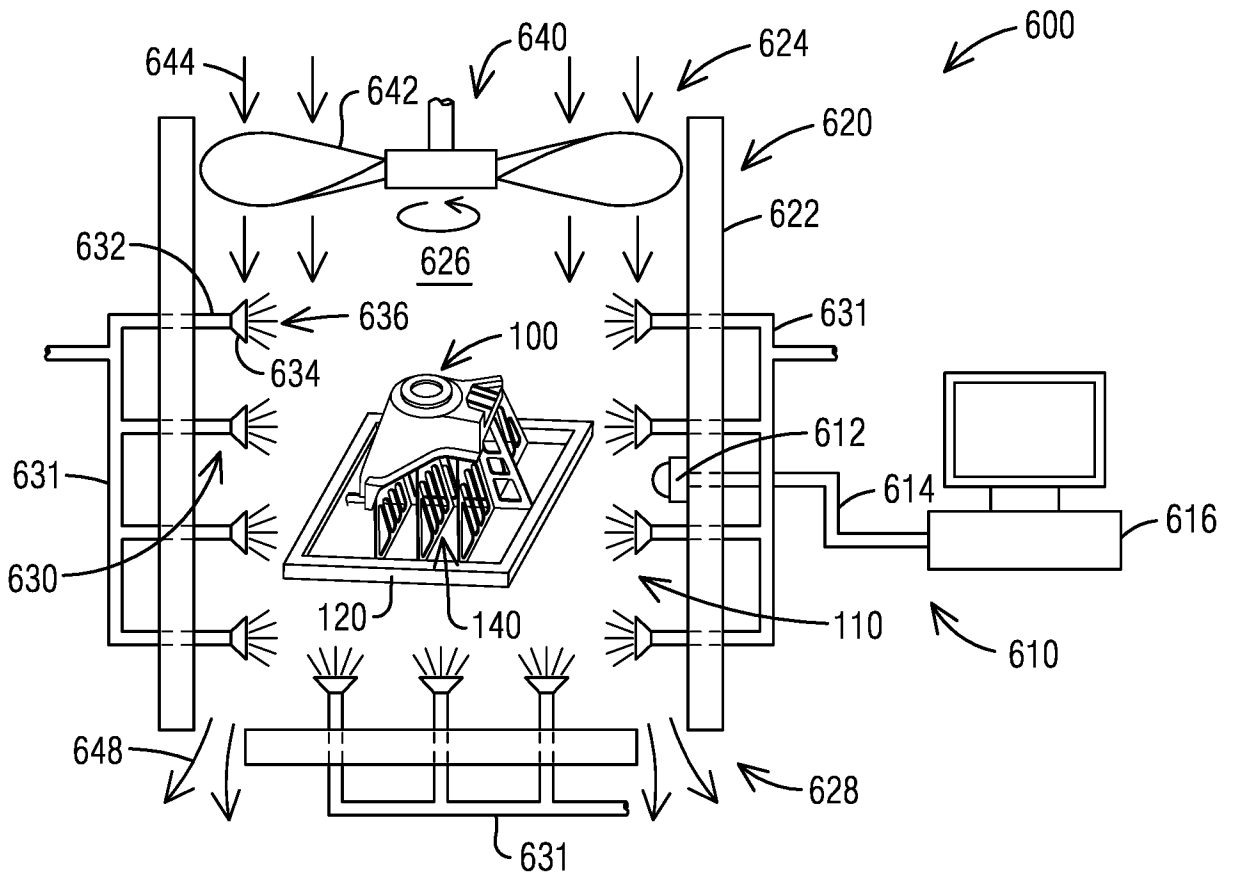


FIG. 19

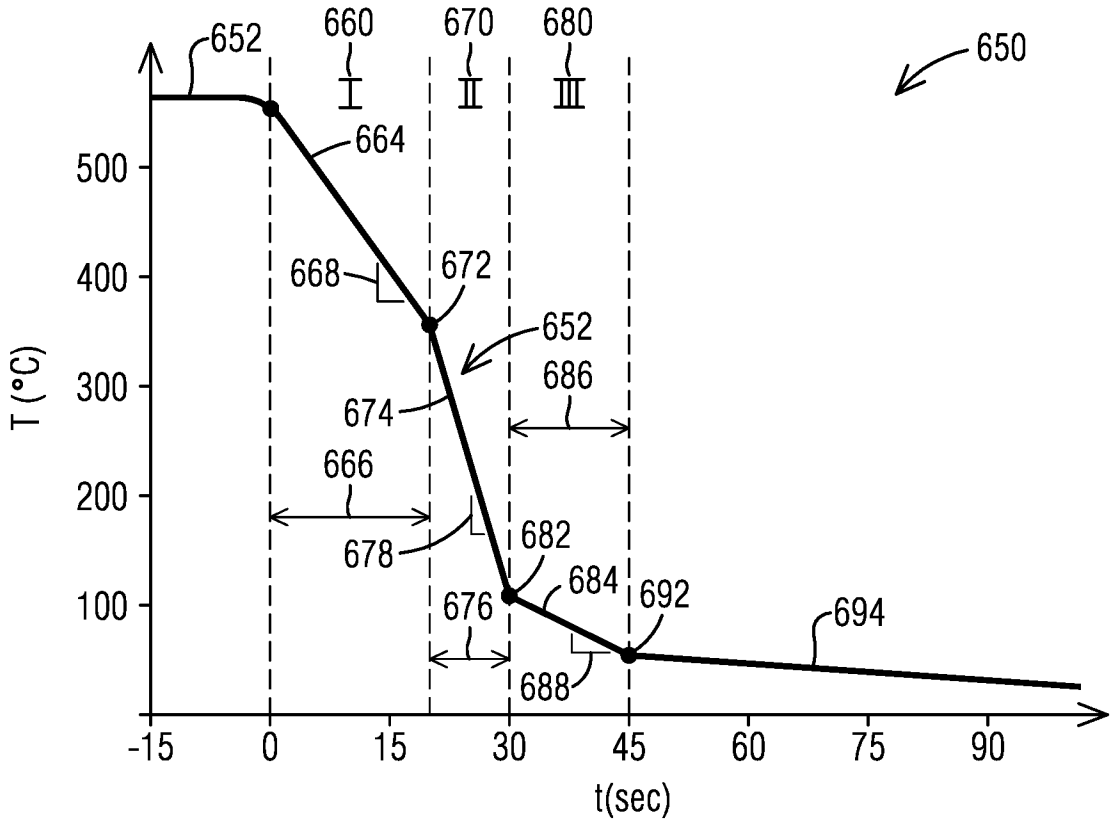


FIG. 20

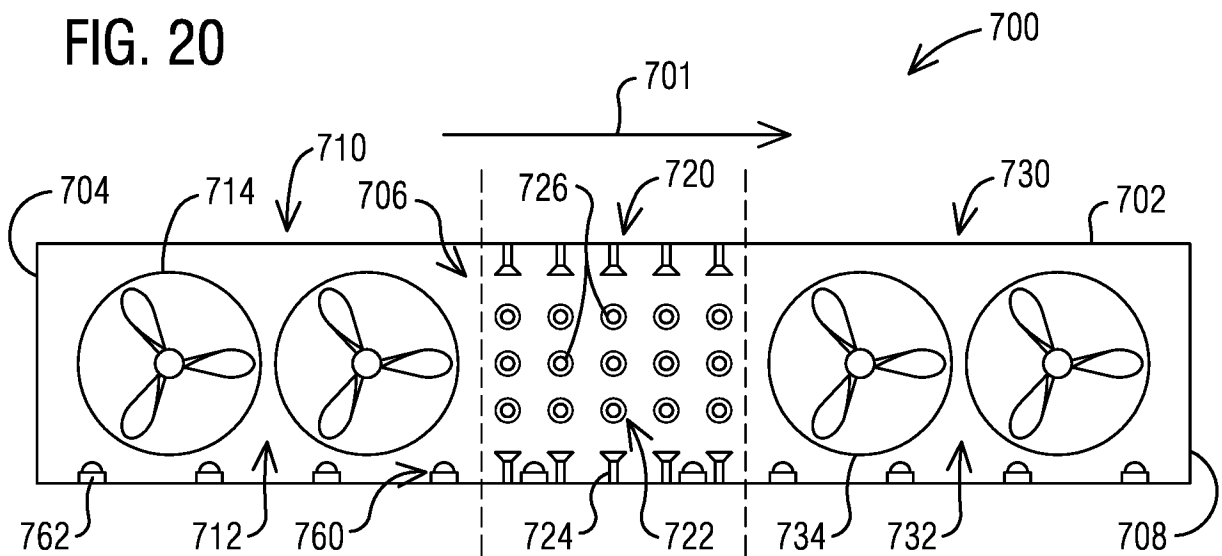


FIG. 21

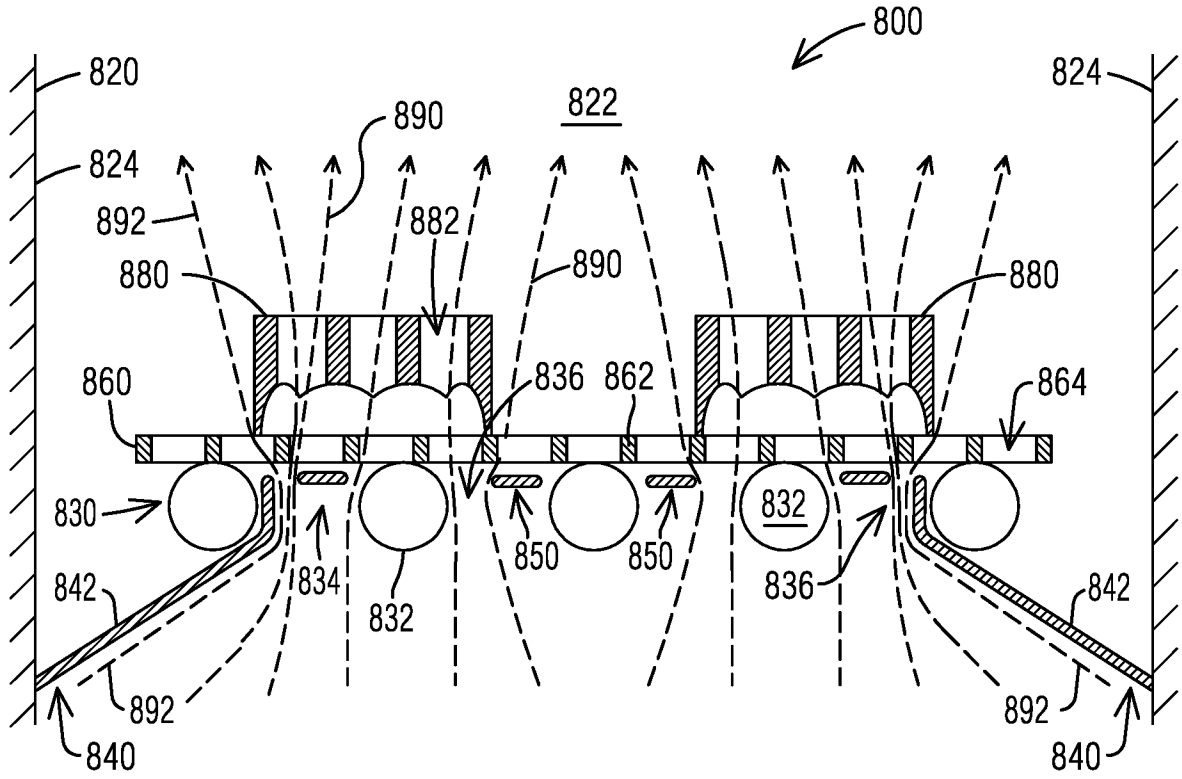


FIG. 22

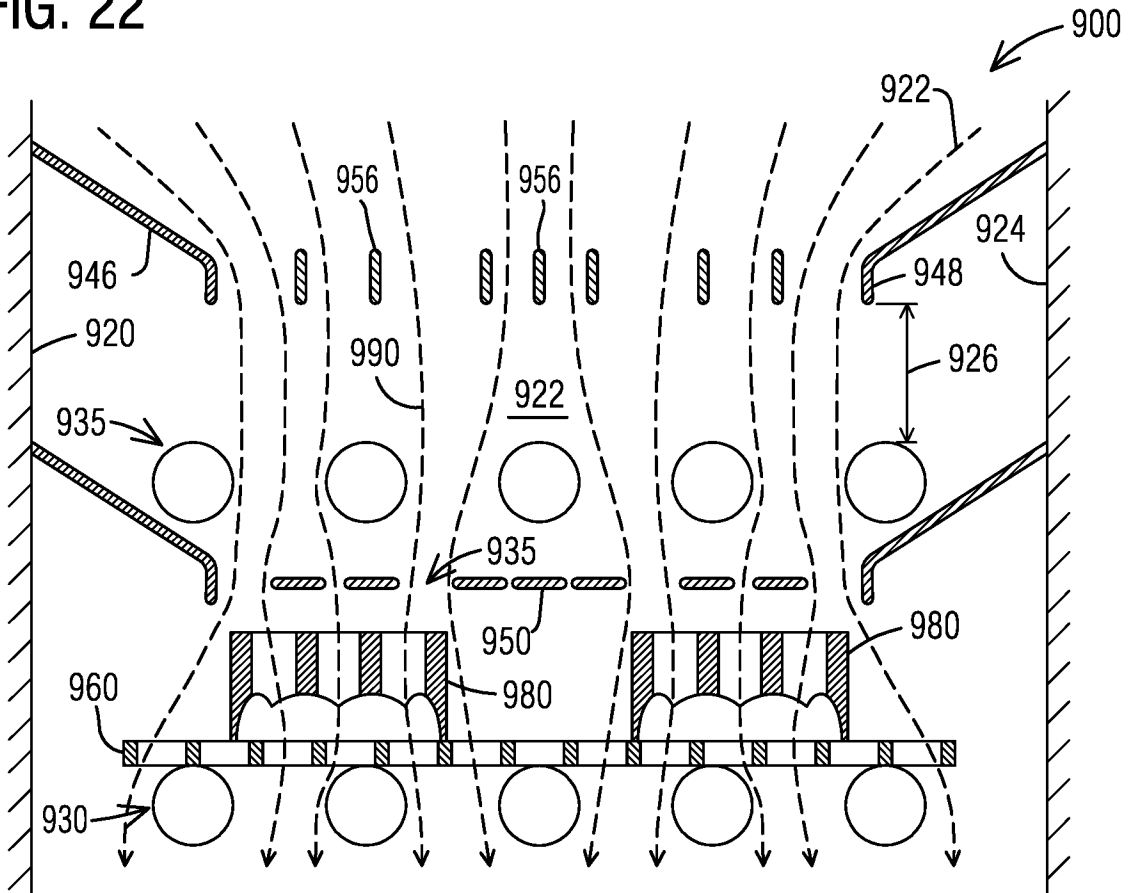
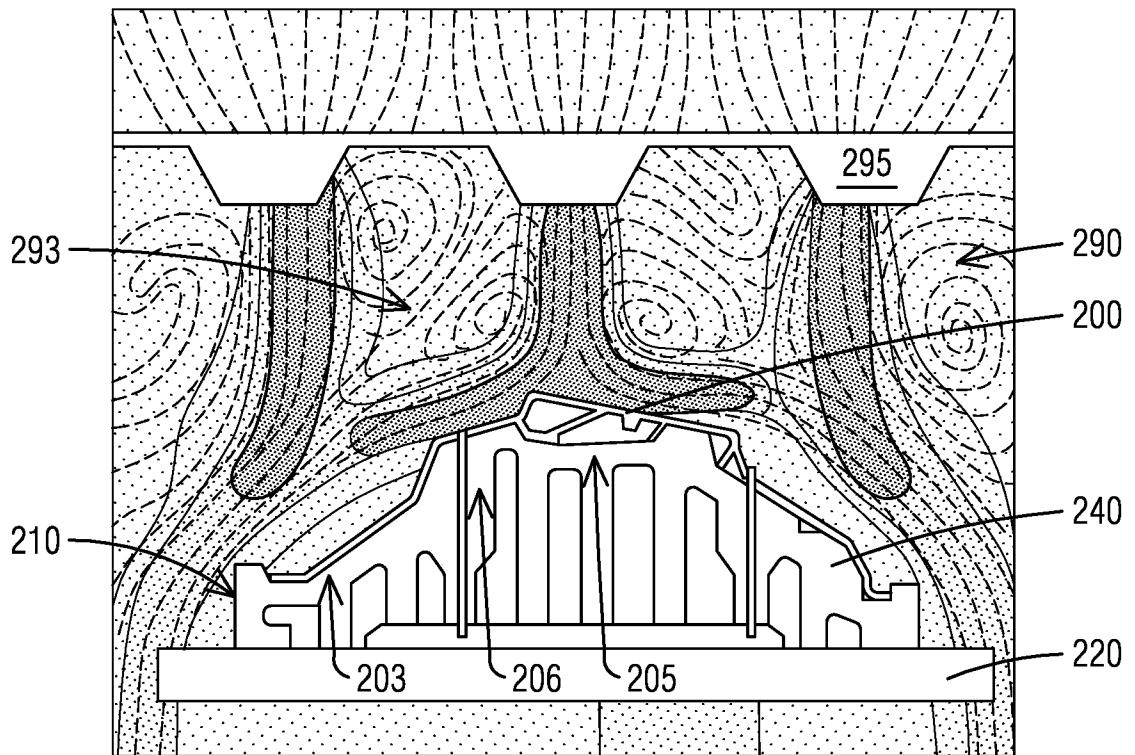


FIG. 23



A. CLASSIFICATION OF SUBJECT MATTER**B22D 17/32(2006.01)i, C21D 9/00(2006.01)i**

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

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
B22D 17/32; C22F 1/00; C22F 1/04; C22F 1/043; C22C 21/02; C21D 9/00; C22C 21/00Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility modelsElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: aluminum casting, thermal treatment, support fixture, 3D, dimension and measure**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6752885 B1 (JERICHOW, ULRICH) 22 June 2004 See abstract and claim 1.	1-22
A	CN 103757574 A (CITIC DICASTAL CO., LTD.) 30 April 2014 See paragraph [0016].	1-22
A	US 5948185 A (KRAJEWSKI et al.) 07 September 1999 See abstract and column 4, lines 9-16.	1-22
A	KR 10-2013-0131052 A (HYUNDAI MOTOR COMPANY) 03 December 2013 See paragraphs [0003]-[0018] and figure 3.	1-22
A	US 2009-0165900 A1 (JUHL, KNUT) 02 July 2009 See paragraphs [0001]-[0019].	1-22

 Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"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

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"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

03 February 2017 (03.02.2017)

Date of mailing of the international search report

03 February 2017 (03.02.2017)

Name and mailing address of the ISA/KR

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Authorized officer

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/058602

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