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CONFORMABLE TOOLING SYSTEMS AND METHODS FOR COMPLEX CONTOUR COMPOSITE PREFORMS

Abstract

A preform tooling arrangement includes a base plate comprising a male die surface and a stripper plate comprising a female die surface. A plurality of perforations are disposed in the base plate and/or the stripper plate. The stripper plate is moveable with respect to the base plate. The preform tooling arrangement is configured to receive a fibrous preform between the male die surface and the female die surface. The preform tooling arrangement is a dual-purpose fixture configured to accommodate z-needling and densification, all while the fibrous preform remains in the same fixture (i.e., the preform tooling arrangement). The perforations are configured to receive one or more textile needles for through thickness reinforcement of the fibrous preform.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a divisional of, and claims priority to and the benefit of, U.S. Non-Provisional patent application Ser. No. 18/155,577, filed Jan. 17, 2023 and titled "CONFORMABLE TOOLING SYSTEMS AND METHODS FOR COMPLEX CONTOUR COMPOSITE PREFORMS," which is incorporated by reference herein in its entirety for all purposes.

FIELD
[0002] The present disclosure relates to systems and methods for manufacturing composites.
BACKGROUND
[0003] Composite bodies are utilized in various industries, including the aerospace industry. Typically, one or more layers of a composite material are stacked together over a mold. The layers may be needled with textile needling to generate a series of z-fibers that extend in the through-thickness direction of the stacked layers. In the case of C/C (carbon/carbon) composites, the shaped preform is then typically moved to one or more other fixtures as it goes through heat treatment and densification processes.
SUMMARY
[0004] According to various embodiments, a preform tooling arrangement is disclosed, comprising a base plate comprising a male die surface, a stripper plate comprising a female die surface, a first plurality of perforations disposed in the base plate, and a second plurality of perforations disposed in the stripper plate. The stripper plate is moveable with respect to the base plate, and the preform tooling arrangement is configured to receive a fibrous preform between the male die surface and the female die surface. Each perforation of the first plurality of perforations can be configured to receive a textile needle. Each perforation of the second plurality of perforations can be configured to receive a textile needle.
[0005] In various embodiments, the base plate comprises two or more base plate sub-components that are configured together to define the male die surface. In various embodiments, the stripper plate comprises two or more stripper plate sub-components that are configured together to define the female die surface.
[0006] In various embodiments, the first plurality of perforations extend from the male die surface to a recess surface in the base plate. In various embodiments, the second plurality of perforations extend from the female die surface to an outer surface in the stripper plate. In various embodiments, each of the second plurality of perforations are sized and configured to receive a textile needle. In various embodiments, each of the first plurality of perforations are sized and configured to receive the textile needle.
[0007] In various embodiments, each of the second plurality of perforations are sized and configured to receive the textile needle. Each of the first plurality of perforations can be sized and configured to receive the textile needle. A center axis of each perforation of the first plurality of perforations can be aligned with a center axis of a corresponding perforation of the second plurality of perforations. Each perforation of the second plurality of perforations disposed in the stripper plate can be configured to receive the textile needle therethrough, whereby the textile needle penetrates through said perforation, through the fibrous preform, and at least partially through the corresponding perforation of the first plurality of perforations disposed in the base plate.

[0008] In various embodiments, the male die surface is a convex surface and the female die surface is a concave surface.
[0009] In various embodiments, the base plate comprises a metallic material, a graphite material, a C/C composite material, and/or a ceramic matrix composite material, e.g., SiC/SiC material among others. In various embodiments, the stripper plate comprises a metallic material, a graphite material, a C/C composite material, and/or a ceramic matrix composite material, e.g., SiC/SiC material among others.
[0010] In various embodiments, the plurality of perforations in the base plate and stripper plate are configured to generate a plurality of perforation zones with different perforation densities, or number of perforations per unit area, and patterns, e.g., a rectangular pattern, a hexagonal pattern, a triangular pattern, a circular pattern, among others. In various embodiments, when the stripper plate is positioned over the base plate, the plurality of perforations in the stripper plate are configured to align with the plurality of perforations in the base plate.
[0011] In various embodiments, the plurality of perforations in the base plate and the stripper plate are configured to create a first zone with a first perforation density, and a second zone with a second perforation density, where the first perforation density is higher than the second perforation density.
[0012] In various embodiments, the plurality of perforations in the base plate and in the stripper plate are configured to create alternating regions of needled and non-needled regions along a direction in the fibrous preform placed between the base plate and the stripper plate.
[0013] In various embodiments, at least one of the first plurality of perforations or the second plurality of perforations comprises a first zone with a first perforation density, and a second zone with a second perforation density, wherein the first perforation density is higher than the second perforation density, and wherein the perforations in the first zone and the second zone are configured to receive the textile needle.
[0014] In various embodiments, the first plurality of perforations and the second plurality of perforations comprise perforated zones alternating with non-perforated zones.
[0015] In various embodiments, at least one of the first plurality of perforations or the second plurality of perforations are arranged in a pattern, and wherein the pattern comprises at least one of a rectangular pattern, a hexagonal pattern, a triangular pattern, or a circular pattern.
[0016] According to various embodiments, a method for manufacturing a needled fibrous composite preform part is disclosed. The method comprises positioning a plurality of layers of a fibrous preform over a base plate, positioning a stripper plate to conform to the base plate and over the plurality of layers, compressing the plurality of layers between the base plate and the stripper plate, disposing a textile needle through a first perforation disposed in the stripper plate and at least partially into the plurality of layers, to form a needled fibrous preform.
[0017] In various embodiments, a method for through thickness needling of a fibrous preform is disclosed and comprises positioning a plurality of layers of a fibrous preform between the base plate and the stripper plate, compressing the plurality of layers between the base plate and the stripper plate, disposing a textile needle through a first perforation disposed in the stripper plate, into the plurality of layers, and at least partially into a corresponding perforation disposed in the base plate to perform a through thickness needling of the fibrous preform.
[0018] According to various embodiments, a method for manufacturing a composite part is disclosed. The method comprises positioning a base plate comprising a first plurality of perforations, positioning a first plurality of layers of a fibrous preform over the base plate, positioning a stripper plate comprising a second plurality of perforations over the first plurality of layers, compressing the first plurality of layers between the base plate and the stripper plate, and providing through-thickness reinforcement in the fibrous preform by disposing a textile needle through at least one perforation of at least one of the first plurality of perforations or the second plurality of perforations and at least partially into the fibrous preform.

[0019] In various embodiments, the method further comprises moving an expanding joint of the stripper plate to a contracted position to conform to the first plurality of layers, disposing the textile needle through a first perforation disposed in the stripper plate and at least partially into the first plurality of layers, removing the stripper plate from the first plurality of layers, positioning a second plurality of layers of the fibrous preform over the first plurality of layers, positioning the stripper plate over the second plurality of layers, and moving the expanding joint of the stripper plate to an expanded position to conform to the second plurality of layers.

[0020] In various embodiments, the method further comprises increasing a thickness of the fibrous preform in response to positioning the second plurality of layers over the first plurality of layers. In various embodiments, the method further comprises disposing the textile needle through the first perforation disposed in the stripper plate, through the second plurality of layers, and at least partially into the first plurality of layers.

[0021] In various embodiments, the expanding joint comprises at least one of a tongue and groove joint, interlocking teeth, or a dovetail.

[0022] In various embodiments, the method further comprises contracting the expanding joint in response to compressing the fibrous preform.

[0023] According to various embodiments, a method for manufacturing a composite preform part, comprising a plurality of layers, is disclosed. The method comprises positioning a fibrous preform with a preform tooling arrangement comprising a base plate and a stripper plate, compressing the fibrous preform between the base plate and the stripper plate, disposing a textile needle through at least one perforation of a plurality of perforations disposed in the stripper plate (or the base plate) and at least partially into the fibrous preform, moving the fibrous preform into a furnace while the fibrous preform remains in the preform tooling arrangement, heating the fibrous preform to a densification temperature while the fibrous preform remains in the preform tooling arrangement, and flowing gases through the perforations and into the fibrous preform to densify the fibrous preform via chemical vapor infiltration.

[0024] In various embodiments, the gases are hydrocarbon gases. It should be understood, however, that the same tooling arrangement may be used to flow other reactant gases to deposit other matrices to produce other composite materials—for example methyltrichlorosilane (MTS) or CH.sub.3Cl.sub.3Si for silicon carbide, BCl.sub.3 and NH.sub.3 for BN, SiCl.sub.4 and hydrocarbon for silicon carbide, SiCl.sub.4 and ammonia for silicon nitride, BCl.sub.3 and hydrocarbon for B.sub.4C, and the like including combinations thereof. In addition, inert, diluting, and/or inhibiting gases such as argon, hydrogen and HCl may be combined with the forementioned reactant gases to control deposition rates and morphology of the deposited compounds.

[0025] In various embodiments, the method further comprises securing the entire assembly, such that the fibrous preform, the base plate, and the stripper plate remain substantially in the same position relative to one another.

[0026] In various embodiments, the gases comprise of hydrocarbons and the densification temperature is in a range from 650° C. to 1425° C. In various embodiments, the densification temperature is in a range from 815° C. to 1040° C.

[0027] In various embodiments, the method further comprises flowing the gases through a second perforation disposed in the base plate and into the fibrous preform to deposit carbon from the gases on and within the fibrous preform. In various embodiments the method further comprises aligning the perforations in the base plate and the stripper plate with the needled regions of the fibrous preform to create paths for gases to flow through the fibrous preform.

[0028] In various embodiments, the method further comprises heating the fibrous preform to a (carbonization and/or heat-treatment) temperature greater than about 1,000 degrees Celsius.

[0029] In various embodiments, the textile needle comprises at least one of a tufting needle or a stitching needle configured to dispose a through thickness reinforcement fibrous filament at least partially through a plurality of layers of the fibrous preform.

[0030] In various embodiments, the fibrous filament for through thickness reinforcement comprises at least one of a fiber already disposed in at least one layer of the plurality of layers of the fibrous preform, a carbon fiber, or an oxidized PAN fiber.
[0031] In various embodiments, the fibrous filament for through-thickness reinforcement further comprises a fugitive fiber, and the method further comprises heating the reinforced fibrous preform while the fibrous preform remains in the tooling preform arrangement to allow the fugitive fiber to burn away and create channels in the through-thickness direction, and densifying the composite by chemical vapor infiltration by flowing gases through the perforations and into the fibrous preform via the channels in the through thickness direction created by the burning away of fugitive fibers.
[0032] In various embodiments, the method further comprises placing a foam layer proximate to the base plate or the stripper plate during the preform needling process. In various embodiments, the method further comprises burning away the foam layer during a chemical vapor infiltration and/or a heat-treatment process.
[0033] In various embodiments, the method further comprises biasing the base plate toward the stripper plate with a clamp comprising a first clamp half moveable with respect to a second clamp half, wherein the first clamp half is configured to move toward the second clamp half while the fibrous preform is in the furnace.
[0034] The foregoing features and elements may be combined in various combinations without exclusivity, unless expressly indicated herein otherwise. These features and elements as well as the operation of the disclosed embodiments will become more apparent in light of the following description and accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0035] The subject matter of the present disclosure is particularly pointed out and distinctly claimed in the concluding portion of the specification. A more complete understanding of the present disclosure, however, may best be obtained by referring to the detailed description and claims when considered in connection with the drawing figures, wherein like numerals denote like elements.
[0036] FIG. **1** is a perspective view of a tooling arrangement with a fibrous preform installed between the stripper plate and the base plate, in accordance with various embodiments;
[0037] FIG. **2** is a perspective view of the tooling arrangement of FIG. **1** during a z-needling process, in accordance with various embodiments;
[0038] FIG. **3** is a perspective view of the stripper plate of the tooling arrangement of FIG. **1**, in accordance with various embodiments;
[0039] FIG. **4** is a perspective view of the base plate of the tooling arrangement of FIG. **1**, in accordance with various embodiments;
[0040] FIG. **5** is a perspective view of the tooling arrangement of FIG. **2** and further including a foam backing layer, in accordance with various embodiments;
[0041] FIG. **6** is a perspective view of the tooling arrangement of FIG. **2** and further including a foam infill layer, in accordance with various embodiments;
[0042] FIG. **7**A is a perspective view of a conformable tooling arrangement with a fibrous preform installed between the stripper plate and the base plate, in accordance with various embodiments;
[0043] FIG. **7**B is a perspective view of a conformable tooling arrangement with a fibrous preform installed between the stripper plate and the base plate, in accordance with various embodiments;
[0044] FIG. **8**A, FIG. **8**B, FIG. **8**C, FIG. **8**D, FIG. **8**E, FIG. **8**F, and FIG. **8**G, illustrate manufacturing steps using the conformable tooling arrangement of FIG. **7**A, in accordance with various embodiments;

[0045] FIG. **9** illustrates a flow chart for a method for manufacturing a composite part made from a multi-layer fibrous preform, in accordance with various embodiments;
[0046] FIG. **10** is a perspective view of a composite clamp, in accordance with various embodiments;
[0047] FIG. **11** is a section view of the composite clamp in an installed position prior to a foam backing layer being removed, in accordance with various embodiments;
[0048] FIG. **12** is a section view of a fibrous preform installed in a tooling arrangement of the present disclosure during a densification process, in accordance with various embodiments;
[0049] FIG. **13** is a perspective view of base plate installed over a support structure, wherein the base plate defines a male die surface having concave and convex sub-regions, in accordance with various embodiments;
[0050] FIG. **14** illustrates a schematic view of a plate (i.e., a base plate and/or a stripper plate) with zones of the plate having perforations disposed at different densities, in accordance with various embodiments;
[0051] FIG. **15**A, FIG. **15**B, FIG. **15**C, and FIG. **15**D illustrate plate aperture/needling penetration patterns comprising a triangular pattern, a square pattern, a hexagonal pattern, a curvilinear pattern, respectively, in accordance with various embodiments; and
[0052] FIG. **16**A, FIG. **16**B, FIG. **16**C, FIG. **16**D, FIG. **16**E, and FIG. **16**F illustrate plate aperture/needling penetration zones comprising a triangular pattern, a square pattern, a hexagonal-triangular (star) pattern, and a curvilinear pattern, a hexagonal pattern, and a linear pattern, respectively, in accordance with various embodiments.

DETAILED DESCRIPTION

[0053] All ranges and ratio limits disclosed herein may be combined. It is to be understood that unless specifically stated otherwise, references to “a,” “an,” and/or “the” may include one or more than one and that reference to an item in the singular may also include the item in the plural.
[0054] The detailed description of exemplary embodiments herein makes reference to the accompanying drawings, which show exemplary embodiments by way of illustration and its best mode, and not of limitation. While these exemplary embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, it should be understood that other embodiments may be realized and that logical, chemical and mechanical changes may be made without departing from the spirit and scope of the invention. For example, the steps recited in any of the method or process descriptions may be executed in any order and are not necessarily limited to the order presented. Moreover, many of the functions or steps may be outsourced to or performed by one or more third parties. Furthermore, any reference to singular includes plural embodiments, and any reference to more than one component or step may include a singular embodiment or step. Also, any reference to attached, fixed, connected or the like may include permanent, removable, temporary, partial, full and/or any other possible attachment option. Additionally, any reference to without contact (or similar phrases) may also include reduced contact or minimal contact.
[0055] As used herein, “fiber volume ratio” means the ratio of the volume of the fibers of the fibrous preform to the total volume of the fibrous preform. For example, a fiber volume ratio of 25% means the volume of the fibers in the fibrous preform is 25% of the total volume of fibrous preform.
[0056] As used herein, the term “fiber density” is used with its common technical meaning with units of g/cm.sup.3 or g/cc. The fiber density may refer specifically to that of the individual fibers in the fibrous preform. The density will be measured, unless otherwise noted, by taking the weight divided by the geometric volume of each fiber. The density may refer to an average density of a plurality of fibers included in a fibrous preform.
[0057] As used herein, “CVI/CVD” may refer to chemical vapor infiltration and/or chemical vapor deposition. Accordingly, CVI/CVD may refer to chemical vapor infiltration or deposition or both.

[0058] As used herein, the term “through thickness reinforcement” includes “needling,” “stitching,” and/or “tufting,” in accordance with various embodiments.

[0059] As used herein, the term “needling” includes traditional needling, “stitching,” and/or “tufting,” in accordance with various embodiments.

[0060] As used herein, CVI/CVD is described herein, in connection with carbon/carbon composite materials as an example, using hydrocarbon gases as the source of carbon. It should be understood, however, that the tooling arrangement of the present disclosure may be used to flow other reactant gases to deposit carbon and other matrices to produce a variety of composite materials—for example, methyltrichlorosilane may be used to infiltrate the composite with a silicon carbide matrix, BCl.sub.3 and ammonia may be used to deposit BN, SiCl.sub.4 and hydrocarbon may be used for silicon carbide, SiCl.sub.4 and ammonia for silicon nitride, or combinations thereof. In addition, inert gases, diluting gases, and/or inhibiting gases such as argon, hydrogen, and HCl may be combined with these gases to control deposition rates and the morphology of the deposited material.

[0061] In various embodiments, the subject matter of this disclosure is generally directed toward fibrous preforms that do not shrink (e.g., carbon fiber); though system and methods of the present disclosure can be utilized with for fibers that exhibit shrinkage, such as OPF, without departing from the scope of the present disclosure.

[0062] In general, there are several methods of manufacturing carbon/carbon (“C/C”) materials depending on the part geometries and the end application performance requirements. One method involves starting with a dry fibrous preform, forming the preform into a shape by laying up on a tool, fixturing the formed shape into suitable graphite fixtures designed to maintain the formed shape but with perforations for allowing gases to flow, and depositing carbon matrix on the fibers by chemical vapor infiltration (CVI) using suitable reactant gases, pressures, and temperatures to fill the voids between the fibers and densify the part. The chemical vapor infiltration cycles may continue, in conjunction with intermediate machining of the surfaces of the preform between infiltration cycles if desired, until the desired part density is achieved. A second method involves the layup and cure of a fabric comprising of carbon fiber and pre-impregnated with a polymer resin. Process steps for forming a shaped part include the steps of laying-up of several layers of the pre-impregnated fabric onto a tool to form a preform, cure of the fiber-reinforced resin preform to form a rigid shape, pyrolysis of the cured shape to decompose or pyrolyze the resin leaving behind carbon fiber and a matrix comprising of carbon or substantially carbon (>85% by weight of the pyrolyzed resin). In this method, additional polymer resin infiltration and pyrolysis cycles may be employed to increase the amount of carbon matrix in the composites, or until the part achieves the desired density. Other methods, including variations and combinations of the above process methods are also in use and may include variations in preform architecture, infiltration resin type, and chemical vapor infiltration conditions. The subject matter of the present disclosure is particularly suited for methods starting with dry fibrous preforms and employing chemical vapor infiltration, but benefits may be realized for the other methods.

[0063] In the foregoing, the fibrous preform comprises a plurality of fabric layers. In various embodiments, the fabric layers comprise a plurality of continuous fiber tows, wherein a fiber tow comprises of a plurality of fiber filaments. These fabric layers may be a weave (e.g., a plain weave, a five harness satin weave, an eight harness satin weave, a basket weave, among others), a braid (e.g., a biaxial braid, a triaxial braid, and the like), and/or a unidirectional tape or fabric layer. The fabric layers may also comprise one or more unidirectional tape or fabric layers wherein each layer is oriented in a different direction relative to the other layer and stitched together to form a stitched non-crimp fabric, as is known in the art. The fibrous preform may further comprise of a fabric layer with discontinuous fibers (e.g., a non-woven fiber mat or veil comprising of discontinuous fibers, chopped fibers and the like). These discontinuous fibers may be randomly oriented or preferentially aligned predominantly in one direction.

[0064] The fibrous preform may be shape formed into a net shape, or near net shape, of the final composite part by laying up in a tool fixture or a closed mold, or the like. Before, during, or immediately after (i.e., before any subsequent processing such as consolidation, densification, and/or densification) being shape formed, the fibrous preform may undergo a through thickness reinforcement process (e.g., Z-needling, tufting, and/or stitching).

[0065] After a fibrous preform is formed into the shape and undergoes a through-thickness reinforcement, the preform is densified. In general, densification involves filling the voids, or pores, of the fibrous preform with additional carbon material. Typically, chemical vapor infiltration and deposition ("CVI/CVD") techniques are used to densify the porous fibrous preform with a carbon matrix. This commonly involves heating the furnace and the carbon preforms, and flowing hydrocarbon gases into the furnace and around and through the fibrous preforms. As a result, carbon from the hydrocarbon gases separates from the gases and is deposited on and within the fibrous preforms. When the densification step is completed, the resulting C/C part has a carbon fiber structure with a carbon matrix infiltrating the fiber structure, thereby deriving the name "carbon/carbon." In some cases, the fibrous preform may be heat-treated prior to densification and/or after densification. The heat-treatment is intended to stabilize or otherwise modify the microstructure of the fiber and/or the matrix, the bonding between the fiber and matrix, drive out any volatiles or undesirable impurities from the composite, or combinations, thereof. These steps of preforming, through-thickness reinforcement, shape-forming, densification and heat-treatment typically involve moving the fibrous preform between various tools for the different manufacturing steps, which can be cumbersome and time consuming.

[0066] C/C parts of the present disclosure may be particularly useful for high temperature aerospace applications. C/C parts of the present disclosure may be especially useful in these applications because of the superior high temperature characteristics of C/C material. In particular, the carbon/carbon material used in C/C parts is a good conductor of heat and is able to dissipate heat generated during high temperature conditions. Carbon/carbon material is also highly resistant to heat damage, and thus, may be capable of sustaining forces during severe conditions without mechanical failure.

[0067] FIG. **1** is a perspective illustration, in accordance with various embodiments, of a preform tooling arrangement **100** (also referred to herein as a conformable preform tooling arrangement). Tooling arrangement **100** includes a base plate **110** and a stripper plate **120**. Base plate **110** may define a male die surface **112** for receiving a fibrous preform **102**. Male die surface **112** may be a convex surface. Stripper plate **120** may define a female die surface **122** for receiving fibrous preform **102**. Female die surface **122** may be a concave surface. In this manner, fibrous preform **102** may conform to a size and geometry of the male die surface **112** and female die surface **122**. FIG. **1** illustrates fibrous preform **102** installed between male die surface **112** and female die surface **122**. Base plate **110** and stripper plate **120** may be made from a metallic material, a graphite material, a C/C composite material, and/or a ceramic matrix composite material, e.g., SiC/SiC material among others.

[0068] During a near net shape lay-up process, one or more sheets or layers of material (e.g., carbon fiber in various embodiments) may be laid up over base plate **110** to form fibrous preform **102**. Stripper plate **120** may be placed over base plate **110** to compress the fibrous preform **102** therebetween.

[0069] FIG. **2** illustrates, in accordance with various embodiments, the tooling arrangement **100** during a needling process. Fibrous preform **102** may undergo a needling process after, or during, the near net shape lay-up process while fibrous preform **102** remains in the same fixture (i.e., between base plate **110** and stripper plate **120**). Stated differently, tooling arrangement **100** may accommodate both near net shape lay-up and needling processes. In this regard, base plate **110** comprises a plurality of perforations **114** (also referred to herein as a first plurality of perforations). Stripper plate **120** similarly comprises a plurality of perforations **124** (also referred to herein as a second plurality of perforations). Perforations **114** and perforations **124** may be configured to align such that the center axis of each perforation **114** aligns with the center axis of a corresponding perforation **124**; though in various embodiments perforations **114** do not align with perforations **124**. In this manner, perforations **114** and perforations **124** may align such that each perforation can receive a needle **150** therethrough during the needling process. In this regard, perforations **114** and/or perforations **124** may be sized to receive a textile needle **150**.

[0070] In various embodiments, the plurality of perforations in the base plate **110** and stripper plate **120** are configured to generate a plurality of perforation zones with different perforation densities, or number of perforations per unit area. For example, momentary reference to FIG. **14**, perforations **114** and/or perforations **124** may generate a first zone A comprising a first density, a second zone B comprising a second density different from that of zone A, and/or a third zone C comprising a third density different from that of zone A and zone B. In various embodiments, perforation density can be greater in some areas to allow for increased needle density (through-thickness reinforcement) in order to increase the interlaminar strength of fibrous preform so as to handle an expected increased interlaminar stress on the final part.

[0071] In various embodiments, the plurality of perforations in the base plate **110** and stripper plate **120** are configured to generate a plurality of patterns, e.g., a rectangular pattern, a hexagonal pattern, a triangular pattern, a circular pattern, among others. For example, with momentary reference to FIG. **15**A through FIG. **15**D, needling penetration patterns may be selected from various shapes at various locations of the fibrous preform, for example depending on the desired through thickness reinforcement and the expected interlaminar stress. FIG. **15**A through FIG. **15**D illustrate plates **410** (i.e., base plate **110** and/or stripper plate **120**) with apertures **440** (each representing a single needle punch). Needling penetrations patterns (i.e., the arrangement of apertures **440**) can comprise a triangular pattern (see FIG. **15**A), a square pattern (see FIG. **15**B), a hexagonal pattern (see FIG. **15**C), and/or a curvilinear pattern (see FIG. **15**D).

[0072] With reference to FIG. **16**A through FIG. **16**F, needling penetration zones may be selected from various shapes at various locations of the fibrous preform depending on the desired through thickness reinforcement and the expected interlaminar stress. FIG. **16**A through FIG. **16**F illustrate plates **510** (i.e., base plate **110** and/or stripper plate **120**) with black areas **442** representing a non-perforated zone (e.g., a non-needled zone) and white areas **444** representing a perforated zone (e.g., a needled zone). In this regard, a first perforated zone may be spaced apart from a second perforated zone, wherein a non-perforated zone is disposed therebetween. Stated differently, perforations in the base plate **110** and/or the stripper plate **120** may form perforated zones alternating with non-perforated zones along the surface of the base plate **110** and/or the stripper plate **120** (e.g., along a direction perpendicular to a center axis of the perforations). Perforation zones (i.e., the areas where the fibrous preform is needled) can comprise a plurality of triangular patterns (see FIG. **16**A), a plurality of square patterns (see FIG. **16**B), a plurality of hexagonal-triangular patterns (see FIG. **16**C), a plurality of curvilinear patterns (see FIG. **16**D), a matrix of hexagonal patterns (see FIG. **16**E), and/or a plurality of linear patterns (see FIG. **16**F). In this regard, the plurality of perforations in the base plate **110** and the plurality of perforations in the stripper plate **120** may be configured to create alternating regions of needled and non-needled regions along a direction in the fibrous preform **102** placed between the base plate **110** and the stripper plate **120**, in accordance with various embodiments.

[0073] With reference to FIG. **2**, the layers of the fibrous preform **102** may be needled perpendicularly to each other (i.e., along the Z-direction) with barbed, textile needles or barbless, structuring needles. In various embodiments, the layers are needled at an angle of between 0° and 60° (e.g., 0°, 30°, 45°, and/or) 60° with respect to the Z-direction to each other. The needling process generates a series of z-fibers through fibrous preform **102** that extend perpendicularly to the fibrous layers. The z-fibers are generated through the action of the needles **150** pushing fibers from within the layer (x-y or in-plane) and reorienting them in the z-direction (through-thickness).

Needling of the fibrous preform may be done as one or more layers are added to the stack or may be done after the entire stack of layers is formed. The needles **150** may also penetrate through only a portion of fibrous preform **102**, or may penetrate through the entire fibrous preform **102**. In addition, resins are sometimes added to fibrous preform **102** by either injecting the resin into the preform following construction or coating the fibers or layers prior to forming the fibrous preform **102**. The needling process may take into account needling parameters optimized to maintain fiber orientation, minimize in-plane fiber damage, and maintain target interlaminar properties. It should be understood that the Z-direction in FIG. **2** corresponds to the location of needles **150**. It should be understood however that the Z-direction is meant to correspond to the direction perpendicular to the plane of the fibrous preform **102** at the location the fibrous preform **102** is being needled. For example, the Z-direction at the sidewall **104** of the fibrous preform **102** would be the direction labeled as the X-direction in FIG. **2**. It should also be understood that the Z-direction may be at an angle to the plane of the fibrous preform **102** at the location the fibrous preform **102** is being needled, and the perforations in the base plate **110** and the stripper plate(s) **120** may be configured to receive the needle at such angle.

[0074] FIG. **3** illustrates, in accordance with various embodiments, a perspective view of the stripper plate **120**. Stripper plate **120** extends longitudinally along a longitudinal centerline **190** of the stripper plate **120** (e.g., along a Y-axis) between and to a first end **130** of the stripper plate **120** and a second end **131** of the stripper plate **120**. The stripper plate **120** extends laterally (e.g., along an X-axis) between and to a first side **132** of the stripper plate **120** and a second side **133** of the stripper plate **120**. The stripper plate **120** extends vertically (e.g., along a Z-axis) between and to a bottom side **134** of the stripper plate **120** and a top side **135** of the stripper plate **120**.

[0075] The stripper plate **120** is configured with at least one die recess **136**; e.g., an aperture such as a pocket, a channel, a groove, etc. The die recess **136** of FIG. **3** extends (e.g., partially) vertically into the stripper plate **120** from one or more bottom surfaces **137** of the stripper plate **120** to female die surface **122** of the stripper plate **120**, where the bottom surfaces **137** of FIG. **3** are arranged on opposing sides of the female die surface **122** at the bottom side **134**. The die recess **136** of FIG. **3** extends longitudinally in (e.g., through) the stripper plate **120**, for example, between and to the stripper plate first end **130** and/or the stripper plate second end **131**. The die recess **136** of FIG. **3** extends laterally in (e.g., within) the stripper plate **120**, for example, between opposing lateral sides of the female die surface **122**.

[0076] The female die surface **122** is a concave or concave-convex surface and may have a curved geometry; e.g., a three-dimensional (3D) curvature. The female die surface **122** of FIG. **3**, for example, has a curved (e.g., arcuate, splined, etc.) cross-sectional geometry in a lateral-vertical reference plane; e.g., an X-Z plane. The female die surface **122** may also have a curved (e.g., arcuate, splined, etc.) cross-sectional geometry in a longitudinal-vertical reference plane; e.g., a Y-Z plane. This recess curvature may change as the female die surface **122**/the die recess **136** extends laterally and/or longitudinally, which may provide the female die surface **122** with a complex 3D curvature. In various embodiments, the recess curvature may remain uniform as the female die surface **122**/the die recess **136** extends laterally and/or longitudinally. The female die surface **122** may be configured without any sharp corners or sharp transitions.

[0077] Stripper plate **120** further comprises an outer surface **138**. In various embodiments, outer surface **138** generally follows the contour of female die surface **122** such that a wall thickness of stripper plate **120** (i.e., the shortest distance from female die surface **122** to outer surface **138** at any particular location) is generally uniform throughout the stripper plate **120**, though in various embodiments the wall thickness of stripper plate **120** may vary. Perforations **124** extend between and to female die surface **122** and outer surface **138** of stripper plate **120**.

[0078] Perforations **114** and/or perforations **124** may comprise round holes of between 0.05 inch and 0.75 inch (1.27 mm-19.05 mm) in diameter. Perforations **114** and/or perforations **124** may cover 50-99% of the base plate **110** and/or stripper plate **120**, respectively. Perforations **114** and/or perforations **124** may be spaced 0.075 inch to 1 inch (1.905 mm-25.4 mm) apart center-to-center, as measured either horizontally, vertically, or diagonally, depending on the location of the perforations **114** being measured. In various embodiments, perforations **114** and/or perforations **123** may constitute 20%-75% of the total surface area of the base plate **110** and/or stripper plate **120**, respectively.

[0079] In various embodiments, stripper plate **120** is a single piece component; though stripper plate **120** may also be formed as a two or more piece component (see FIG. **7**A through FIG. **8**G).

[0080] FIG. **4** illustrates, in accordance with various embodiments, a perspective view of the base plate **110**. Base plate **110** extends longitudinally along a longitudinal centerline **191** of the base plate **110** (e.g., along a Y-axis) between and to a first end **140** of the base plate **110** and a second end **141** of the base plate **110**. The base plate **110** extends laterally (e.g., along an X-axis) between and to a first side **142** of the base plate **110** and a second side **143** of the base plate **110**. The base plate **110** extends vertically (e.g., along a Z-axis) between and to a bottom side **144** of the base plate **110** and a top side **145** of the base plate **110**.

[0081] The base plate **110** may be configured with at least one recess **146**; e.g., an aperture such as a pocket, a channel, a groove, etc. The recess **146** of FIG. **4** extends (e.g., partially) vertically into the base plate **110** from one or more bottom surfaces **147** of the base plate **110** to a recess surface **116** of the base plate **110**, where the bottom surfaces **147** of FIG. **4** are arranged on opposing sides of the recess surface **116** at the bottom side **144**. The recess **146** of FIG. **4** extends longitudinally in (e.g., through) the base plate **110**, for example, between and to the base plate first end **140** and/or the base plate second end **141**. The recess **146** of FIG. **4** extends laterally in (e.g., within) the base plate **110**, for example, between opposing lateral sides of the recess surface **116**.

[0082] The male die surface **112** is a convex or concave-convex surface and may have a curved geometry; e.g., a three-dimensional (3D) curvature. The male die surface **112** of FIG. **4**, for example, has a curved (e.g., arcuate, splined, etc.) cross-sectional geometry in a lateral-vertical reference plane; e.g., an X-Z plane. The male die surface **112** may also have a curved (e.g., arcuate, splined, etc.) cross-sectional geometry in a longitudinal-vertical reference plane; e.g., a Y-Z plane. This recess curvature may change as the male die surface **112**/the recess **146** extends laterally and/or longitudinally, which may provide the male die surface **112** with a complex 3D curvature. In embodiments, the recess curvature may remain uniform as the male die surface **112**/the recess **146** extends laterally and/or longitudinally. The male die surface **112** may be configured without any sharp corners or sharp transitions.

[0083] In various embodiments, recess surface **116** generally follows the contour of male die surface **112** such that a wall thickness of base plate **110** (i.e., the shortest distance from recess surface **116** to male die surface **112** at any particular location) is generally uniform throughout the base plate **110**, though in various embodiments the wall thickness of base plate **110** may vary. Perforations **114** extend between and to male die surface **112** and recess surface **116** of base plate **110**.

[0084] In various embodiments, base plate **110** is a single piece component; though base plate **110** may also be formed as a two or more piece component (see FIG. **7**A through FIG. **8**G). For example, with momentary reference to FIG. **8**A through FIG. **8**G) base plate **110** can comprise two or more pieces (e.g., first half **211** and second half **212**) moveable with respect to one another to conform to the shape and/or size of the fibrous preform **102** and/or support structure **105**. It should be understood that although illustrated as having a first half **211** and a second half **212**, base plate **110** can comprise any number of base plate sub-components that are configured together to define a male die surface **112** (see FIG. **6**). Moreover, it is contemplated herein that the male die sub-components can interlock with one another similar to the stripper plate sub-components **281**, **282**, as described herein.

[0085] FIG. **5** illustrates, in accordance with various embodiments, tooling arrangement **100** further including a foam backing layer **160** disposed between fibrous preform **102** and base plate **110**.

Foam backing layer **160** may be thick enough such that the needles **150** penetrate only into the foam backing layer **160** and not into the base plate **110**. This arrangement tends to allow for more flexibility in base plate **110** design, as the perforations **114** do not need to be aligned with the needling operation. In various embodiments, foam backing layer **160** provides structural support for the fibrous preform **102** during the z-needling process.

[0086] FIG. **6** illustrates, in accordance with various embodiments, tooling arrangement **100** further including a foam infill layer **170** disposed in the perforations **114** of base plate **110**. In this manner, the needles **150** may penetrate through the foam infill layer **170**. Providing foam infill layer **170** in perforations **114** tends to allow for more flexibility in base plate **110** design. Providing foam infill layer **170** in perforations **114** tends to aid in keeping needle orientation aligned (i.e., to keep the needles **150** from deflecting). For example, perforations **114** in base plate **110** can be larger for CVI densification while still supporting the needling operation. In various embodiments, foam infill layer **170** provides structural support for the fibrous preform **102** during the z-needling process.

[0087] FIG. **7**A illustrates, in accordance with various embodiments, a conformable tooling arrangement **200**. Tooling arrangement **200** may be similar to tooling arrangement **100**, except that stripper plate **220** includes flexible joints **226** such that the stripper plate **220** may expand and conform to the shape of the fibrous preform **102** as layers are added to the fibrous preform **102**. Equipping stripper plate **220** with flexible joints **226** tends to ensure compression is appropriately applied to the fibrous preform **102** at each stage of manufacturing.

[0088] In various embodiments, stripper plate **220** can comprise two or more pieces (e.g., first half **281** and second half **282**) moveable with respect to one another to conform to the shape and/or size of the fibrous preform **102**. It should be understood that although illustrated as having a first half **281** and a second half **282**, stripper plate **220** can comprise any number of stripper plate sub-components that are configured together to define a female die surface **122** (see FIG. **6**). In various embodiments, first half **281** comprises a first plurality of interlocking teeth **283** and second half comprises a second plurality of interlocking teeth **284**. First plurality of interlocking teeth **283** may be configured to interlock with second plurality of interlocking teeth **284**. In various embodiments, first plurality of interlocking teeth **283** interlock with second plurality of interlocking teeth **284** to lock the first half **281** from sliding longitudinally with respect to second half **282**.

[0089] In various embodiments, the flexible joint **226** may be selected from a variety of joints-tongue and groove, interlocking teeth, dovetail, etc. In various embodiments, the flexible joint **226** comprises a tongue and groove connection between a first half **281** of the stripper plate **220** and a second half **282** of the stripper plate **220**. The tongue and groove connection can be utilized to mitigate out of plane (e.g., the vertical direction or along the Z-direction) movement of the first half **281** with respect to the second half **282**.

[0090] In various embodiments, flexible joint **226** comprises a dovetail connection. The dovetail connection may lock the first half **281** from sliding laterally (along the X-direction) with respect to the second half **282**. In this manner, first half **281** and/or second half **282** may be replaced with different sized halves to accommodate different sized preforms **102**.

[0091] FIG. **7**B illustrates, in accordance with various embodiments, a conformable tooling arrangement **201**. Conformable tooling arrangement **201** may be similar to conformable tooling arrangement **200**. Flexible joint **227** comprises interlocking teeth whereby the first half **281** is slidably coupled to second half **282**. For example, the first plurality of interlocking teeth **285** and the second plurality of interlocking teeth **286** may lock the first and second halves **281**, **282** from sliding longitudinally (along the Y-direction) with respect to one another, but may allow the first and second halves **281**, **282** to freely slide laterally (along the X-direction) with respect to one another.

[0092] For example, FIG. **8**A through FIG. **8**G illustrates a C/C part manufacturing process using conformable tooling arrangement **201**.

[0093] With reference to FIG. **8**A, the base plate **110** may be placed onto a mount or support structure **105**.

[0094] With reference to FIG. **8**B, the fibrous preform **102** is placed on the base plate **110**. In various embodiments, a first layer of the fibrous preform **102** is placed on the base plate **110** in FIG. **8**B. The fibrous preform **102** can conform to a shape of the base plate **110**.

[0095] With reference to FIG. **8**C, the stripper plate **220** is placed on top of the fibrous preform **102**. In various embodiments, first half **281** is placed over fibrous preform **102** and second half **282** is placed over fibrous preform **102**. In FIG. **8**C, the flexible joint **227** is moved to a contracted position, whereby the flexible joint **227** is closed or nearly closed (i.e., the first half **281** is moved against, or close to, the second half **282**).

[0096] With reference to FIG. **8**D, the stripper plate **220** can be removed and additional plies or layers can be added to the fibrous preform **102**. In this regard, the overall size of fibrous preform **102** can increase.

[0097] With reference to FIG. **8**E, the stripper plate **220** can again be placed over the fibrous preform **102**, though this time the first half **281** may be further spaced apart from the second half **282** due to the increased volume of the fibrous preform **102**. Although the flexible joint **227** is illustrated at a central location of the stripper plate **220**, flexible joint **227** may additionally or alternatively be placed at the corners (e.g., radii) of the stripper plate **220**. In various embodiments, the fibrous preform **102** is compressed between the base plate **110** and the stripper plate **220**. In various embodiments, the additional plies or layers can be successively needled each time a new layer is added, as desired (see FIG. **2**). FIG. **8**E illustrates the flexible joint **227** of the stripper plate **220** moved to an expanded position to conform to the plurality of layers of the fibrous preform **102**. In the expanded position, the first half **281** is moved away (e.g., laterally) from the second half **282** to accommodate the increased thickness of the fibrous preform **102**.

[0098] With reference to FIG. **8**F, the steps described with respect to FIG. **8**B through FIG. **8**E may be repeated as desired, using the flexible joint **227** in stripper plate **220** to adjust to different thicknesses of the fibrous preform **102**.

[0099] With reference to FIG. **8**G, the conformable tooling arrangement **201**, together with fibrous preform **102**, can be loaded into a furnace for densification as desired. In various embodiments, a composite clamp **500** (see FIG. **10** and FIG. **11**) can be installed over the base plate **110** and stripper plate **220** before placing the conformable tooling arrangement **201** into the furnace.

[0100] FIG. **9** is a flow chart for a method **400** for manufacturing a carbon-carbon component, in accordance with various embodiments. For ease of description, the method **400** is described below with reference to FIG. **1** through FIG. **6**. The method **400** of the present disclosure, however, is not limited to use of the exemplary preform tooling arrangement **100** of FIG. **1** through FIG. **6**.

[0101] In step **402**, the fibrous preform **102** is provided. Fibrous preform **102** may be configured as a multi-layered preform. Fibrous preform **102** may be draped over base plate **110**, for example when fibrous preform **102** is made from one or more layers of carbon fiber sheets. Fibrous preform **102** may be placed over base plate **110** and compressed into the desired shape and fiber volume (e.g., using stripper plate **120**, for example when fibrous preform **102** is made from one or more layers of fabrics or sheets. The stripper plate **120** may be placed over the fibrous preform **102** to compress the fibrous preform **102** between the stripper plate **120** and the base plate **110** (see FIG. **1** for example).

[0102] In step **404**, a the fibrous preform **102** undergoes a z-needling process in situ (i.e., while the fibrous preform **102** is installed between the stripper plate **120** and the base plate **110**). In various embodiments, and in preparation for the z-needling process, foam backing layer **160** disposed between fibrous preform **102** and base plate **110** (see FIG. **5**) or foam infill layer **170** is disposed in the perforations **114** of base plate **110** (see FIG. **6**). During the z-needling process, textile needles **150** are inserted through perforations **124** and at least partially into fibrous preform **102** to displace fibers in fibrous preform **102** to extend in the z-direction, thereby achieving desired interlaminar properties of the fibrous preform **102**. In various embodiments, during the z-needling process, textile needles **150** are inserted through perforations **124** and completely through fibrous preform **102**. In various embodiments, during the z-needling process, textile needles **150** are inserted through perforations **124**, completely through fibrous preform **102**, and at least partially into foam backing layer **160**. In various embodiments, during the z-needling process, textile needles **150** are inserted through perforations **124**, completely through fibrous preform **102**, and at least partially into foam infill layer **170**. In various embodiments, during the z-needling process, textile needles **150** are inserted through both perforations **124** and perforations **114** (e.g., in embodiments where perforations **114** and perforations **124** are aligned).

[0103] In various embodiments, a sizing agent is added to the fibrous preform **102** during the shape-forming process. For example, a sizing agent comprising a fluid and/or fluid vapor such as water, steam, and/or polyvinyl alcohol may be applied to the fibrous preform **102** (e.g., before being shape formed). Adding the sizing agent to the fibrous preform **102** may dampen the fibers thereof which tends to relax the fibers of the fibrous preform, thereby aiding in the bending, forming, and/or stretching of the fibrous preform. Adding the sizing agent to the fibrous preform **102** may also help to reduce wrinkling of the fibrous preform. Sizing may help to protect the fiber from handling damage and provide lubricity allowing the fibers to slide easily during the lay-up, needling and/or preforming/compaction process. Sizing agents of the present disclosure include water soluble polymers. The sizing agent may comprise a water solution. The sizing agent may comprise long chain alcohols such as polyvinyl alcohols, modified starch, cellulose gum such as carboxymethyl cellulose, modified wax, acrylates, and/or mixtures thereof. In various embodiments, up to about 700 mL (23.7 fluid oz) of water or more may be applied to the fibrous preform **102**, though the amount of water is a variable parameter based on a variety of factors, including the size and volume of the fibrous preform **102**. In various embodiments, approximately 1 milliliter (ml) of water may be added for every 2.5 cubic inches of fibrous preform (1 ml/2.5 in.sup.3), wherein the term approximately as used in this context can only mean±0.5 ml. Stated differently, between 0.5 ml and 1.5 ml of water may be added to the fibrous preform for every 2.5 cubic inches of fibrous preform. However, it should be understood that other amounts of water or sizing agent may be added to the fibrous preform without departing from the scope of the present disclosure. Moreover, the fibrous preform may be preconditioned in a humidity chamber at a humidifying temperature (e.g., between 100° F. (37.8° C.) and 200° F. (93.3° C.)) and a relative humidity (e.g., between 75% and 90% humidity). Adding the sizing agent to the fibrous preform **102** may tend to reduce wrinkling of the fibrous preform **102** and support stabilizing the preform into the desired shape during the needling and shape-forming stages. In this manner, the fibrous preform **102** may be compressed to the desired fiber volume more easily and formed to shape using heat, moisture, pressure, stripper plate **120**, and base plate **110**, into the contoured shapes as desired for a particular C/C part application. In various embodiments, the sizing agents may also provide lubricity between the fibrous preform **102** and stripper plate **120** and/or between the fibrous preform **102** and base plate **110**, preventing the fibrous preform **102** from sticking to the stripper plate **120** and/or the base plate **110**, respectively.

[0104] In various embodiments, foam backing layer **160** or foam infill layer **170** may be made of a foam material that burns cleanly during the carbonization/heat-treatment or densification process (depending on which process is used immediately following z-needling). In this regard, foam backing layer **160** or foam infill layer **170** may burn away cleanly during the carbonization/heat-treatment or densification process-leaving just the fibrous preform **102**, stripper plate **120**, and base plate **110**. To accommodate shrinking of the fibrous preform **102** and/or burning away of the foam (particularly when foam backing layer **160** is used), graphite and/or C/C composite clamps may be used to maintain compression on fibrous preform **102**. For example, with reference to FIG. **10**, a composite clamp **500** is illustrated, in accordance with various embodiments. Clamp **500** includes a first clamp half **502** and a second clamp half **504** moveable with respect to the first clamp half **502**. A guide shaft **506** may extend from first clamp half **502** and into a guide slot or aperture **508** disposed in second clamp half **504**. Guide shaft **506** may align second clamp half **504** with first clamp half **502** and guide relative translation of second clamp half **504** with respect to first clamp half **502**. FIG. **11** is a section view of clamp **500** installed over base plate **110** and stripper plate **120**. In this illustrated embodiment, foam backing layer **160** is installed between base plate **110** and fibrous preform **102**. In this installed position, and prior to heat-treatment or densification, second clamp half **504** is spaced apart from first clamp half **502** by a distance **590** which is greater than the thickness **591** of foam backing layer **160**. In this manner, clamp **500** may close (i.e., second clamp half **504** moves toward first clamp half **502**, thereby closing, or partially closing, the distance **590**) as the foam backing layer is burned away in response to being heated to heat-treatment or densification temperatures. Moreover, distance **590** may be configured to accommodate shrinking of fibrous preform **102**. During the heat-treatment and/or densification steps, a force—represented by arrow **592**—may be applied to clamp **500** to maintain compression on the fibrous preform **102** to set preform thickness and/or fiber volume as the foam backing layer **160** burns away, for example using a dead weight, a press, or the like. In this regard, the second clamp half **504** may be biased toward the first clamp half **502** while the preform tooling arrangement **100** is in the heat-treatment and/or densification furnace.

[0105] In various embodiments, after the z-needling process, foam backing layer **160** or foam infill layer **170** may be washed away in a water bath. In this regard, the foam backing layer **160** and/or foam infill layer **170** may comprise a washable foam. Removing the foam before heat-treatment and/or densification may tend to be desirable over burning away the foam in the furnace.

[0106] In step **406**, the fibrous preform **102** undergoes a heat-treatment process, particularly when the fibrous preform **102** is not already entirely, or nearly entirely (e.g., greater than 99%), carbon and contains no to very small amounts (<1%) sizing agents or resin binders. In this regard, step **406** may be optional. Stated differently, step **406** may be skipped when fibrous preform **102** is made of higher purity or high temperature carbon fibers.

[0107] Step **406** may be performed with fibrous preform **102** secured in compression within preform tooling arrangement **100**, particularly where preform tooling arrangement **100** is made from a graphite material, a C/C material, or other material suitable for withstanding heat-treatment and densification temperatures. The fibrous preform **102** (now a shaped body) may be heat treated to fully convert the fibrous preform **102** to a carbon preform. In various embodiments, fibrous preform **102** together with preform tooling arrangement **100** may be placed in a furnace for heat-treatment. The heat-treatment process may be employed to convert the fibers of the fibrous preform **102** into pure carbon fibers and to drive off any volatile species present in the fibrous preform **102**, for example, moisture and oxygen, hydrogen or nitrogen species present in the sizing agents. As used herein only “pure carbon fibers” means carbon fibers comprised of at least 95% carbon. Since the heat-treatment step helps to drive off most of the elements other than carbon from the fibrous preform, the heat-treatment process is sometimes referred to as carbonization. As used herein, heat-treatment and carbonization may be used interchangeably. The carbonization or heat-treatment process is distinguished from the densification process described below in that the densification process involves infiltrating the pores of the fibrous preform **102** and depositing a carbon matrix within and around the carbon fibers of the fibrous preform **102**, and the heat treatment or carbonization process refers to the process of converting the fibers of the fibrous preform **102** into pure carbon fibers.

[0108] The shape-formed fibrous preform **102** may be carbonized/heat-treated by placing the shape-formed fibrous preform **102** in a furnace with an inert atmosphere. In general, the carbonization process involves heating the shape-formed fibrous preform **102** in a furnace to a carbonization/heat-treatment temperature greater than about 1,000 degrees Celsius (1,832 Fahrenheit). Typically, an inert atmosphere of nitrogen, argon or a vacuum is provided in the furnace during the carbonization/heat-treatment process. The heat of the furnace converts the fibers to purer carbon fibers and drives off other chemicals. Although it is sometimes preferred that the fibers in the heat-treated fiber preform be 100% carbon fiber, it is generally acceptable for a less than full conversion to take place. The resulting heat-treated fiber preform generally has the same fibrous structure as the fibrous preform **102** before heat-treatment. During heat-treatment, the total mass and the total fiber volume in each fibrous preform **102** is typically reduced in proportion to the non-carbon compounds present in the fibrous preform **102** and driven off during the heat-treatment process.

[0109] In step **408**, the fibrous preform **102** (or heat-treated fibrous preform if step **406** is utilized) undergoes a CVI densification process. Step **408** may be performed after step **406** (or after step **404** when fibrous preform **102** is made from carbon fibers and step **406** is omitted). In this regard, the same preform tooling arrangement **100** may be conveniently used for shape-forming, z-needling, carbonization (optional), and CVI densification.

[0110] In general, densification involves filling the voids, or pores, of the fibrous preform **102** with additional carbon material. This may be done using the same furnace used for heat-treatment or a different furnace. Typically, chemical vapor infiltration and deposition ("CVI/CVD") techniques are used to densify the porous fibrous preform **102** with a carbon matrix. This commonly involves heating the furnace and the carbonized preforms, and flowing hydrocarbon gases (e.g., at least one of methane, ethane, propane, butane, and/or the like, as described herein) into the furnace and around and through the fibrous preforms. In various embodiments, the CVI/CVD process may include a temperature gradient. In various embodiments, the CVI/CVD process may include a pressure gradient. In various embodiments, the CVI/CVD process may include a temperature and a pressure gradient.

[0111] CVI/CVD densification may be conducted in a vacuum or partial vacuum (e.g., at pressures of 1-15 torr) or in an inert atmosphere at a densification temperature in the range from about 650° C. to about 1425° C. (1,200° F. to about 2,600° F.), and in various embodiments in a range of about 900° C. to about 1100° C. (1,652° F. to about 2,012° F.), and in various embodiments in a range of about 815° C. to about 1040° C. (1,500° F. to about 1,900° F.), and in various embodiments in the range of up to about 1,000° C. (1,832° F.) (wherein the term about in this context only means+/−100° C.) for a period of time in the range from about 150 hours to about 650 hours, and in various embodiments, in the range from about 300 hours to about 500 hours (wherein the term about in this context only means+/−24 hours).

[0112] As a result, carbon from the hydrocarbon gases separates from the gases and is deposited on and within the fibrous preforms. Typically, the densification process is continued until the preform reaches a density in the range from 1.6 to 1.9 grams per cubic centimeter (g/cc), and in various embodiments, a density of approximately 1.80 g/cc. When the densification step is completed, the resulting C/C part has a carbon fiber structure with a carbon matrix infiltrating the fiber structure, thereby deriving the name "carbon/carbon."

[0113] FIG. **12** is, in accordance with various embodiments, a section view of a portion of the preform tooling arrangement **100** during a densification process. Perforations **124** in stripper plate **120** and perforations **114** in base plate **110** aid in allowing the hydrocarbon gases **195** to infiltrate throughout the fibrous preform **102** during densification. In this regard, perforations **114** and/or perforations **124** may serve a dual purpose for z-needling and densification. In this regard, step **408** may further include flowing hydrocarbon gases **195** through perforations **114** and/or perforations **124** and into fibrous preform **102**.

[0114] After a first CVI/CVD cycle of 50 to 500 hours, an intermediate heat treat may be performed, in the same furnace. This heat treat (>1600° C.) serves to dimensionally stabilize the fibrous preform **102**, increase its thermal properties, and increase its porosity for subsequent densification. The fibrous preform **102** may then be taken out of the tool-assembly. That is the fibrous preform **102** with the CVI/CVD carbon may be separated from the stripper plate **120** and the base plate **110** and any clamps **500**. The outer surfaces of the fibrous preform **102** may be machined to open the porosity further, to help allow for final density to be achieved using only one more CVI/CVD cycle, with or without the tooling assembly around the fibrous preform **102**. Part densities after first machining may be in the range of 1.4 to 1.7 g/cc, depending on the part thickness, overall size, and placement within the furnace. Typical, average density range is 1.55-1.65 g/cc.

[0115] The densification process may be continued until the preform reaches a desired density, for example in the range from 1.7 to 1.9 grams per cubic centimeter (g/cc), and in various embodiments, a density of approximately 1.80 g/cc. The CVI/CVD process may be continued with the fibrous preform **102** removed from the perforated graphite fixture. In this manner, the outer surfaces of the fibrous preform **102** may be more directly exposed to the gas flow. Moreover, the fibrous preform **102** may be machined in between carbon CVI densification processes (e.g., between fixtured carbon CVI densification and non-fixtured carbon CVI densification and/or between successive non-fixtured carbon CVI densification processes). Machining (e.g., grinding, sanding, milling, grit blasting, etc.) the fibrous preform **102** may be performed to achieve a final desired part shape. Machining the fibrous preform **102** may be performed to expose voids, or pores, of the fibrous preform **102** so as to facilitate infiltration with additional carbon material during subsequent carbon CVI densification. When the densification step is completed, and the desired density is achieved, the resulting C/C part has a carbon fiber structure with a carbon matrix infiltrating the fiber structure, thereby deriving the name "carbon/carbon."

[0116] Following the CVI/CVD densification process, the C/C part may undergo a final heat treatment (FHT) process. This may be done using the same furnace used for densification or a different furnace. If done using the same furnace, the flow of hydrocarbon gases would be stopped following the end of the densification process and the temperature increased. FHT may be conducted in a vacuum or partial vacuum (e.g., at pressures of 1-15 torr) or in an inert atmosphere at a temperature in the range from about 1200° C. to about 2600° C. (2,921° F. to about 4,712° F.), and in various embodiments in the range from about 1400° C. to about 2200° C. (2,552° F. to about 3,992° F.) (wherein the term about in this context only means+/−100° C.) for a period of time in the range from about 4 hours to about 14 hours, and in various embodiments, in the range from about 8 hours to about 12 hours (wherein the term about in this context only means+/−2 hours). In various embodiments, the FHT process imparts high temperature dimensional stability to the final C/C part. In various embodiments, the FHT process imparts desired thermal properties associated with thermal shock such as high thermal conductivity, high heat capacity, and/or high emissivity.

[0117] With reference to FIG. **13**, a base plate **310** is illustrated installed over a support structure **105**, in accordance with various embodiments. Although illustrated as have base plate sub-components **311**, **312**, base plate **310** may also comprise a single piece base plate, or may comprise any number of base plate sub-components, in accordance with various embodiments. In various embodiments, the male die surface **312** may feature sub-regions that are locally concave together with regions that are convex along a direction of the die surface. Stated differently, a first sub-region **391** (along the Y-direction; also referred to as the longitudinal direction) of base plate **310** can be convex and a second sub-region **392** (along the Y-direction) of base plate **310** can be concave. In various embodiments, the male die surface **312** may be convex in one direction (see first sub-region **391** along the Y-direction) and concave in a different direction of the male die surface **312** (see third sub-region which is concave along the X-direction).

[0118] Systems and methods are provided. In the detailed description herein, references to "various embodiments", "one embodiment", "an embodiment", "an example embodiment", etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described. After reading the description, it will be apparent to one skilled in the relevant art(s) how to implement the disclosure in alternative embodiments.

[0119] Benefits, other advantages, and solutions to problems have been described herein with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any elements that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as critical, required, or essential features or elements of the invention. The scope of the invention is accordingly to be limited by nothing other than the appended claims, in which reference to an element in the singular is not intended to mean “one and only one” unless explicitly so stated, but rather “one or more.” Moreover, where a phrase similar to “at least one of A, B, or C” is used in the claims, it is intended that the phrase be interpreted to mean that A alone may be present in an embodiment, B alone may be present in an embodiment, C alone may be present in an embodiment, or that any combination of the elements A, B and C may be present in a single embodiment; for example, A and B, A and C, B and C, or A and B and C. Furthermore, no element, component, or method step in the present disclosure is intended to be dedicated to the public regardless of whether the element, component, or method step is explicitly recited in the claims. No claim element herein is intended to invoke 35 U.S.C. 112 (f) unless the element is expressly recited using the phrase “means for.” As used herein, the terms “comprises,” “comprising,” or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

Claims

1. A method for manufacturing a composite part, the method comprising: positioning a base plate comprising a first plurality of perforations; positioning a first plurality of layers of a fibrous preform over the base plate; positioning a stripper plate comprising a second plurality of perforations over the first plurality of layers; compressing the first plurality of layers between the base plate and the stripper plate; and providing through-thickness reinforcement in the fibrous preform by disposing a textile needle through at least one perforation of at least one of the first plurality of perforations or the second plurality of perforations and at least partially into the fibrous preform.

2. The method of claim 1, further comprising: moving an expanding joint of the stripper plate to a contracted position to conform to the first plurality of layers; disposing the textile needle through a first perforation disposed in the stripper plate and at least partially into the first plurality of layers; removing the stripper plate from the first plurality of layers; positioning a second plurality of layers of the fibrous preform over the first plurality of layers; positioning the stripper plate over the second plurality of layers; and moving the expanding joint of the stripper plate to an expanded position to conform to the second plurality of layers.

3. The method of claim 2, further comprising: increasing a thickness of the fibrous preform in response to positioning the second plurality of layers over the first plurality of layers; and disposing the textile needle through the first perforation disposed in the stripper plate, through the second plurality of layers, and at least partially into the first plurality of layers.

4. The method of claim 2, wherein the expanding joint comprises at least one of a tongue and groove joint, interlocking teeth, or a dovetail.

5. A method for manufacturing a composite part, the method comprising: positioning a fibrous preform with a preform tooling arrangement comprising a base plate and a stripper plate, wherein at least one of the base plate or the stripper plate comprises a plurality of perforations; compressing the fibrous preform between the base plate and the stripper plate; disposing a textile needle through at least one perforation of the plurality of perforations and at least partially into the fibrous preform; moving the fibrous preform into a furnace while the fibrous preform remains in the preform tooling arrangement; heating the fibrous preform to a densification temperature while the fibrous preform remains in the preform tooling arrangement; and flowing gases through the plurality of perforations and into the fibrous preform to densify the fibrous preform via chemical vapor infiltration.

6. The method of claim 5, wherein the textile needle comprises at least one of a tufting needle or a stitching needle configured to dispose a through thickness reinforcement fibrous filament at least partially through a plurality of layers of the fibrous preform.

7. The method of claim 6, wherein the fibrous filament for through thickness reinforcement comprises at least one of: a fiber already disposed in at least one layer of the plurality of layers of the fibrous preform; a carbon fiber, or an oxidized PAN fiber.

8. The method of claim 7, wherein the fibrous filament for through-thickness reinforcement further comprises a fugitive fiber, and wherein the method further comprises: heating the reinforced fibrous preform while the fibrous preform remains in the tooling preform arrangement to allow the fugitive fiber to burn away and create channels in the through-thickness direction; and densifying the composite by chemical vapor infiltration by flowing gases through the perforations and into the fibrous preform via the channels in the through thickness direction created by the burning away of fugitive fibers.

9. The method of claim 5, further comprising: placing a foam layer proximate to at least one of the base plate or the stripper plate during the preform needling process; and burning away the foam layer during at least one of a chemical vapor infiltration or a heat-treatment process.

10. The method of claim 5, further comprising biasing the base plate toward the stripper plate with a clamp comprising a first clamp half moveable with respect to a second clamp half, wherein the first clamp half is configured to move toward the second clamp half while the fibrous preform is in the furnace.