conditions can form a silicon carbide crystal. The carbon source and the silicon source form the silicon carbide, for example, in the presence of heat. The microwaves, e.g., the microwaves from the microwave module 106, can cause the carbon and silicon sources to react to form a silicon carbide compound or precursor. The microwaves can also cause crystal growth of the resulting silicon carbide compound or the precursor.

In some implementations, if the feed materials contain separate carbon and silicon sources, the apparatus 100 optionally includes a heat source that adds heat to the feed material 110 to cause the reaction between the silicon source and the carbon source to form the silicon carbide. The heat source causes the reaction to form the silicon carbide compound, and then the microwave module 106 can cause crystallization of the silicon carbide compound.

The ceramic component that goes on to form the ceramic crystal can be relatively transparent to the radiation from the radiation source 120. In addition, because the curable component includes a photoinitiator sensitive to the radiation from the radiation source, the curing radiation enables the curable component to be cured without inducing a chemical reaction in the ceramic component to crystallization of the ceramic component.

The curable component can be about between 1% and 30% by mass (e.g., between 1% and 3% by mass, between 3% and 30% by mass, between 10% and 30% by mass, between 25% to 30% by mass, etc.) of the feed material 110. The ceramic component can be about 10% to 98% by mass (e.g., between 10% and 30% by mass, between 30% and 50%, between 50% and 75% by mass, between 75% and 98% by mass, etc.) of the feed material 110.

Also shown in FIGS. 1 and 2, the microwave module 106 includes a microwave source 122, controllable by the control system 114, that applies microwaves directed toward the platform 112. The microwaves can vaporize the curable component of the feed material 110. The microwaves can also cause crystallization of the feed material 110 to form the ceramic part.

In some examples, the microwaves vaporize the photosensitive polymer, when the photosensitive polymer is in its cured state. The microwaves cause crystallization of the ceramic component in the feed material 110. The microwaves can cause nucleation of the ceramic component. The microwave source 122, by emitting the microwaves toward the feed material 110, can also cause growth of the ceramic crystal transparent to the microwaves.

To enable the microwaves to vaporize the curable component while inducing formation of the ceramic crystal, the curable component and the ceramic component can be differentially

transparent to the microwaves. The ceramic crystal formed during the crystallization can have a transparency to the microwaves 400% to 2000% greater than a transparency to the microwaves of the curable component after the curable component has been cured. In other words, the ceramic crystal can have a transparency to the microwaves 400% to 2000% greater than a transparency to the microwaves of the cured polymer.

The microwaves emitted by the microwave source 122 can be frequency controlled such that the microwaves vary over a range of frequencies. For example, the microwave source 122 can be connected to a frequency controller 124 that modulates the frequencies of the microwaves. In some examples, the frequency controller 124 is part of the controller 116.

The microwave source 122 can be controlled by the frequency controller 124 such that the microwave source 122 sequentially emits the microwaves at each of the frequencies selected between the predetermined range of frequencies. The microwaves can be emitted at, for example, 100 to 5000 different frequencies between the predetermine range of frequencies (e.g., 100 to 3000 different frequencies, 3000 to 5000 frequencies, 4000 to 4200 frequencies, approximately 4096 frequencies). The predetermined range of frequencies can be between 5.8 and 6.8 gigahertz. In some examples, the microwave source 122 emits the microwaves at each of the frequencies for approximately 25 microseconds. In some implementations, the microwave source 122 emits the microwaves at each of the frequencies for 5 to 45 microseconds (e.g., 5 to 25 microseconds, 15 to 35 microseconds, or 25 to 45 microseconds). However, in some examples, the microwaves can also be emitted at a fixed frequency, for example, between 5.8 and 6.8 gigahertz.

In some examples, the microwaves emitted by the microwave source 122 can cause multiple ceramic crystals within a layer of the feed material 110 to form. The microwaves can add sufficient heat to the feed material 110 to vaporize the cured polymer and sinter the multiple ceramic crystals formed during the crystallization process. The multiple ceramic crystals can thus be sintered together to form a solid mass of the ceramic crystals.

In some cases, the microwave source 122 applies microwaves to cover the entire usable build area of the platform 112. In this case, the microwave source 122 can be activated to apply the microwaves after the additive manufacturing module 104 has dispensed and cured all of one or more layers of the feed material 110. Optionally, the microwave source 122 can be activated after the additive manufacturing module 104 has completed one or more layers of the feed

material 110 but before the additive manufacturing module has begun dispensing and curing operations of another layer of the feed material 110. In some implementations, the microwave source 122 emits microwaves that cause crystal growth and polymer vaporization through layers underneath the top layer of the feed material 110. In such cases, the microwave source 122 can be activated after multiple layers of the feed material 110 have been dispensed and cured.

In some implementations, the additive manufacturing module 104 and the microwave module 106 are both coupled to linear actuators that move the modules 104, 106 horizontally relative to the platform 112. The platform 112 can be held in a horizontal position within the enclosure 102 as the modules 104, 106 move through the enclosure 102 relative to the platform 112.

The microwave source 122 is movable relative to the platform 112. In some examples, the platform 112 is coupled to a linear actuator that is capable of moving the platform 112 through the enclosure 102. After the additive manufacturing module 104 has dispensed and cured the layers 108, the linear actuator can move the platform 112 from beneath the additive manufacturing module 104 to beneath the microwave module 106 to prepare the layers 108 to receive the microwaves from the microwave module 106.

The microwave source 122 optionally emits the microwaves through a microwave horn 125 to direct the microwaves over the length and width of the platform 112. FIGS. 3A to 3E depict various examples of microwave horns 125a-125e that could be used with the microwave source 122. The microwave horns 125a-125e include a flaring metal waveguide shaped like a horn to direct microwaves in a beam toward the platform 112. The horn 125a-125e can be shaped to guide the microwaves emitted by the microwave source 122 to a portion of the platform 112. The aperture at the end of the flaring metal waveguide can determine the pattern of electric fields (E-field) and magnetic fields (H-fields) at the mouth of the horn 125a-125e. The microwave horns 125a-125e can have different flare angles as well as different expansion curves (e.g., elliptic, hyperbolic, and other expansion curves) in the E-field and H-field directions to enable emission of a range of microwave beam profiles.

FIG. 3A depicts a pyramidal horn 125a having a shape of a four-sided pyramid with a rectangular cross section that flares outwardly. The pyramidal horn 125a can be used with rectangular waveguides and radiate linearly polarized radio waves. FIG. 3B depicts an E-plane horn 125b that is flared in the direction of the electric or E-field in the waveguide. FIG. 3C

depicts an H-plane horn 125c that is a sectoral horn. A sectoral horn is a pyramidal horn with only one pair of sides flared and the other pair parallel. The sectoral horn produces a fan-shaped beam, which is narrow in the plane of the flared sides, but wide in the plane of the parallel sides. The H-plan horn 125c is a sectoral horn flared in the direction of the H-field in the waveguide. FIG. 3D depicts a conical horn 125d having the shape of a cone with a circular cross section. The conical horn 125d can be used with cylindrical waveguides. FIG. 3E depicts an exponential or scalar horn 125e with curved sides, in which the separation of the sides increases as an exponential function of length. The scalar horn 125e can have pyramidal or conical cross sections. The scalar horn 125e can have minimum internal reflections, almost constant impedance, and other characteristics over a wide frequency range.

Optionally, the apparatus 100 also includes a sensing system 126 that detects properties of the feed material 110 as the feed material 110 undergoes the various processes performed by the additive manufacturing module 104 and the microwave module 106. The sensing system 126 can include an optical sensor 128. The sensor 128 is, for example, an infrared radiation sensor 128 that detects infrared radiation emitted by the feed material 110 on the platform 112. The sensor 128 determines, for example, a temperature of the layers 108 of the feed material 110 to enable the control system 114 to monitor the operations of the modules 104, 106. In some examples, the sensor 128 is an infrared emitter and detector that can be used to determine the surface texture of the feed material 110 on the platform 112.

In some implementations, the apparatus 100 includes a window 130 along the enclosure 102 that enables optical monitoring of the feed material 110. The window 130 can be, for example, a quartz window with a conductive mesh that provides a faraday cage. This enables the window 130 to be opaque to the microwaves emitted by the microwave module 106. While the quartz is transparent to the microwaves, the faraday cage prevents the microwaves from travelling through the window 130. In this regard, the window 130 allows for optical monitoring without allowing microwaves to escape into the environment outside of the apparatus 100. In some examples, the optical sensor 128 is positioned outside of the enclosure 102 and is able to emit an optical signal towards the platform 112 through the window 130. Thus, the window 130 can be transparent to the optical signal emitted by the optical sensor 128 but be opaque to the microwaves emitted by the microwave module 106. The window 130 is, for example, transparent to infrared light emitted by the optical sensor.

control the dispenser 118 of the additive manufacturing module 104 to dispense the layer of the feed material 110. The first layer of the feed material 110 can be uniformly dispensed (400A) on the platform 112.

The first layer of the feed material is then cured through application (400B) of ultraviolet light. The control system 114, for example, operates the additive manufacturing module 104 to emit the ultraviolet light toward the platform 112 to cause the first layer of the feed material 110 dispensed at operation 400A to be cured, thereby stabilizing the feed material 110. The control system 114 can activate the radiation source 120 of the additive manufacturing module 104 to emit the radiation to cure the curable component of the feed material 110.

A second layer of feed material is then dispensed (400C). The control system 114 continues controlling the additive manufacturing module 104 to dispense (400C) the layer of the feed material 110 by controlling the dispenser 118. Prior to dispensing (400C) the second layer, the control system 114 can control an actuator coupled with the platform 112 and/or the dispenser 118 to change the vertical position of the dispenser 118 relative to the platform 112. In particular, the control system 114 can control the actuator to increase the distance between the dispenser 118 and the platform 112 so that the dispenser 118 can be positioned above the first layer dispensed and can dispense the second layer on top of the first layer.

In some examples, the dispensing operation 400A and the applying operation 400B can be repeated several times before the dispensing operation 400C is executed. For example, if the radiation source 120 is a UV light laser, the control system 114 can sequentially execute the dispensing operation and the applying operation 400B to dispense and cure a portion of the first layer of the feed material 110. Repetition of these operations 400A, 400B enables the control system 114 to operate the additive manufacturing module 104 to dispense and cure the entire first layer of the feed material 110. For example, the dispenser 118 can dispense a predetermined number of voxels of the feed material 110, and the predetermined number of voxels of the feed material 110 can form a portion of the layer of the feed material 110. The portion of the layer of the feed material 110 can have an area sufficiently small such that the beam of light from the radiation source 120 can cover the entire area. In some examples, the radiation source 120 emits a beam of light covering the entire usable build area. In such cases, the control system 114 executes the dispensing operation 400A to dispense an entire first layer of

platform 112. While the additive manufacturing module 104 is able to dispense the feed material 110 and direct the UV light toward the platform 112, the microwave module 106 can be positioned relative to the platform 112 to be unable to emit the microwaves toward the platform 112. The control system 114 can, for example, control one or more linear actuators coupled to one or more of the dispenser 118 and/or the radiation source 120, the platform 112, and the microwave source 122. In these cases, in preparation for operation 400E, the control system 114 may operate the modules 104, 106 and/or the platform 112 such that the microwave module 106 can emit the microwaves toward the platform 112. The additive manufacturing module 104 can also be positioned relative to the platform 112 such that the additive manufacturing module 104 is unable to dispense and cure the feed material 110 on the platform 112.

In the process 400 depicted in FIG. 4, the microwaves are applied (400E) after multiple layers are dispensed and cured. In some examples, the microwaves are applied after each layer of the feed material 110 is dispensed and cured.

In some examples, the ceramic part is formed from two layers of the feed material 110, and thus, only the operations 400A to 400E may be necessary. While only operations 400A to 400E are shown, the process 400 can be repeated multiple times such that more than two layers of the feed material 110 can be dispensed, cured, and crystallized. The dispensing (400A, 400C), applying UV light (400B, 400D), and applying microwaves (400E) operations can be repeated to create a ceramic part formed from three or more layers of the feed material 110.

In some examples in which three or more layers of the feed material 110 are dispensed and cured, the control system 114 can control the additive manufacturing module 104 to dispense and cure the curable component of each of the layers of the feed material 110. After dispensing and curing the feed material 110 for all of the layers to be dispensed, the control system 114 can then control the microwave module 106 to apply the microwaves to vaporize the curable component of all of the layers simultaneously. The microwaves, in this case, can thus be capable of penetrating through the top layer and at least two layers beneath the top layer.

In some implementations of the additive manufacturing apparatus 100, as described herein, the additive manufacturing module 104 and the dispenser 118 can dispense a single type of feed material 110 on the platform 112. Optionally, the additive manufacturing module 104 and the dispenser 118 dispense an additional type of feed material. The dispenser 118 can dispense

both the first feed material and the second feed material. The first feed material can be dispensed from a first opening of the dispenser 118, and the second feed material can be dispensed from a second opening of the dispenser 118.

The two feed materials each includes the curable component and the ceramic component. The first and second feed materials differ in that the first feed material may include a greater density of the ceramic component than density of the ceramic component in the second feed material. The ratio of the ceramic component to the curable component in the first feed material differs from the ratio of the ceramic component to the curable component in the second feed material. In some examples, the ratio of the first feed material is 600 % to 1000% greater than the ratio of the second feed material.

In the first feed material, the ratio of the curable component to the ceramic component by mass can be between 1 to 10 and 1 to 3. In the second feed material, the ratio of the curable component to the ceramic component by mass can be between 1 to 3 and 1 to 1. The ratio of the curable component to the ceramic component in the first feed material can be between 10% and 1000% (e.g., between 10% and 200%, between 200% and 600%, between 600% and 1000%) greater than the ratio of the curable component to the ceramic component in the second feed material.

In some examples, the ceramic component of the first feed material includes polymethylsilane and the ceramic component of the second feed material includes $[CH_3(CH=CH)SiO]_4$. In some examples, the ceramic component of the first feed material includes $[SiH_{1.26}(CH_3)_{0.6}(CH_2CH=CH_2)_{0.14}CH_2]_n$ and the ceramic component of the second feed material includes Cp_2TiCl_2 and/or vinyl ferrocene.

If only one feed material is used, the feed material can include ceramic crystal seeds to increase the rate of crystallization and improve uniformity of crystallization. If more than one feed material is used, optionally, one or both of the feed materials include ceramic crystal seeds. The two feed material can include a different density of ceramic crystal seeds. The first feed material dispensed in the first and third layers can have a greater density of ceramic crystal seeds than the density of the ceramic crystal seeds of the second feed material dispensed in the second layer. In some implementations, the first feed material includes ceramic crystal seeds, while the second feed material does not include ceramic crystal seeds.

Because the first feed material has a proportion of the ceramic component greater than a proportion of the ceramic component in the second feed material, crystallization of the first feed material can lead to ceramic crystals larger than ceramic crystals formed from crystallization of the second feed material. The additive manufacturing apparatus 100 may utilize the difference in grain sizes between the ceramic crystals of the first and second feed materials to promote bonding and sintering between layers of the feed materials. Heterogeneity of the grain sizes between layers can improve strengths of bonds between the layers of the feed materials. FIGS. 5A and 5B show an example of a process 500 that uses two types of feed materials. In particular, FIG. 5A schematically depicts a graph of dispensing and applying operations and a relative duration of time for execution of each of these operations. FIG. 5B shows a flowchart of the process 500.

The process 500 begins with a first layer of feed material is dispensed (500A). The first layer is formed from the first feed material. UV radiation is then applied (500B) to the first layer of the first feed material. A second layer of feed material is then dispensed (500C). The second layer is formed from the second feed material. UV radiation is then applied (500D) to the second layer of the second feed material. Finally, a third layer of feed material is dispensed (500E), the third layer being formed from the first feed material. The UV radiation is then applied (500F) to the third layer of the first feed material. At operation 500G, microwaves are applied to cause crystallization of the ceramic component in the feed materials in each of the first, second, and third layers. The dispensing operations 500A, 500C, 500E are similar to the dispensing operations 400A, 400C described herein, except the feed material dispensed in the dispensing operation 500C differs from the feed material dispensed in the operations 500A, 500E, whereas the feed material dispensed in the operations 400A, 400C are the same.

As shown in FIG. 5A, the operation time for each of these operations 500A to 500F can be similar. The operation time of the operation 500G may be relatively longer than the operation time of each of the operation times of the operations 500A to 500F. Because the operations 500A to 500F are each limited to dispensing and curing feed material in a single layer while the operation 500G entails application of microwaves to multiple layers, the operation 500G may require a longer operation time so that the microwaves can cause sufficient crystallization within each of the first, second, and third layers. The operation time of the operation 500G may be two to forty times longer than the operation time of each of the operations 500A to 500F. In some

examples, the duration of the time that the UV radiation is applied can be between 0.1 seconds per 0.01 square meter per layer and 1 second per 0.01 square meter per layer. In some cases, the duration of time that the microwaves are applied do not depend on the number of layers. The duration of time can be, for example, between 1 seconds and 20 seconds.

The sequential operations 500A to 500F enables the second layer formed from the second feed material to be sandwiched between two layers formed from the first feed material. In particular, the first layer of the first feed material (dispensed and cured in the operations 500A and 500B) is below the second layer of the second feed material (dispensed and cured in the operations 500C and 500D). The third layer of the first feed material (dispensed and cured in the operations 500E and 500F) is above the second layer of the second feed material. This arrangement of the two feed materials results in a layer of feed material having a lower density of the ceramic component positioned between two layers of higher density of the ceramic component.

When the microwave source 122 applies (500G) the microwaves to the first, second and third layers, the microwave source 122, by applying the microwaves, can cause crystallization of the ceramic components of the first and second feed materials, thereby causing crystallization in each of the first, second, and third layers. The layer having the lower density of the ceramic component, i.e., the second layer, forms a smaller ceramic crystal relative to the ceramic crystals formed in the two layers having the higher density of the ceramic component, i.e., the first and third layers. The ceramic crystals formed in the first and third layers are, for example, 300% to 2000% larger than the ceramic crystals formed in the second layer (e.g., 300% to 1200%, 400% to 2000%, 1200% to 2000% larger than the ceramic crystals formed in the second layer). The ratio of the sizes of the ceramic crystals can depend on the difference in density of the ceramic component in the first and second feed materials.

The microwaves, in addition to causing crystallization, can also cause sintering between the ceramic crystals. The ceramic crystal or crystals formed in the second layer can be sintered to the ceramic crystal or crystals formed in the first and third layers due to the application of the microwaves. The smaller grain size of the ceramic crystals formed in the second layer relative to the grain size of the ceramic crystals formed in the first and third layers can result in stronger bonds between ceramic crystals. In particular, the smaller grain size can result in the