US 20140072816A1

(19) **United States**
(12) **Patent Application Publication**
Lee

(10) **Pub. No.: US 2014/0072816 A1**
(43) **Pub. Date: Mar. 13, 2014**

(54) **BOND LAYERS FOR CERAMIC OR CERAMIC MATRIX COMPOSITE SUBSTRATES**

(75) Inventor: **Kang N. Lee**, Zionsville, IN (US)

(73) Assignee: **ROLLS-ROYCE CORPORATION**, Indianapolis, IN (US)

(21) Appl. No.: **14/006,848**

(22) PCT Filed: **Mar. 22, 2012**

(86) PCT No.: **PCT/US2012/030174**

§ 371 (c)(1),
(2), (4) Date: **Nov. 25, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/466,556, filed on Mar. 23, 2011.

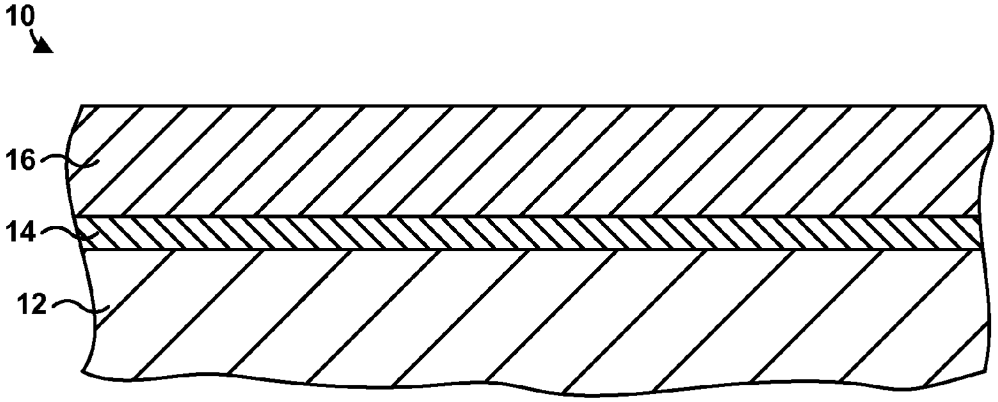
Publication Classification

(51) **Int. Cl.**
F01D 25/00 (2006.01)

(52) **U.S. Cl.**
CPC ***F01D 25/005*** (2013.01)
USPC **428/448**; 427/255.15

(57) **ABSTRACT**

A bond layer may include a composition that may be stable at temperatures above about 1410° C. An article may include a substrate, a bond layer formed on the substrate, and an overlayer formed over the bond layer. In some examples, the bond layer may include a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide. In other examples, the bond layer may include Si, an alkali metal oxide, and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide. In other examples, the bond layer may include B_2O_3.



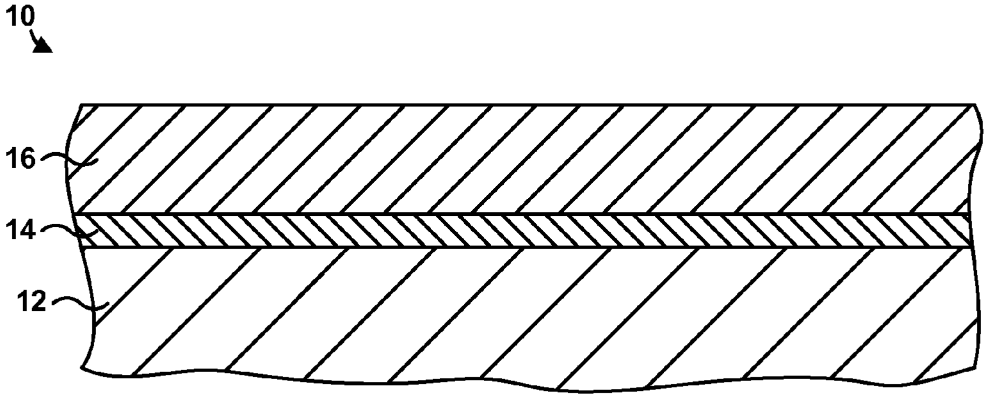


FIG. 1

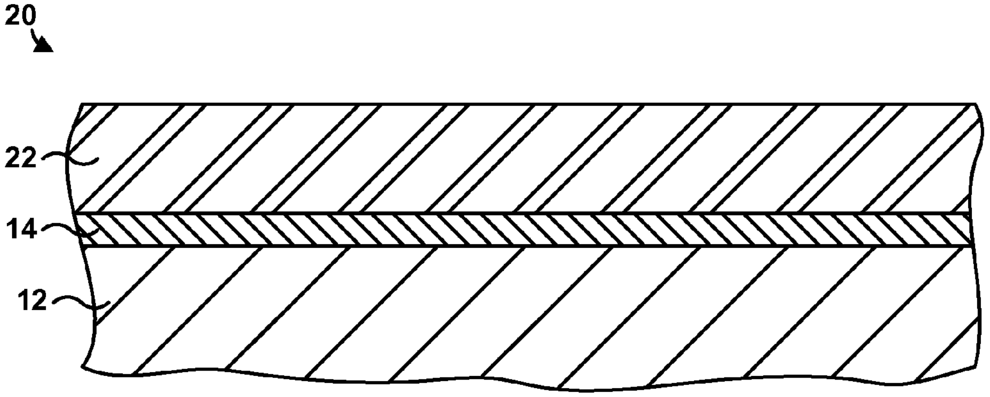


FIG. 2

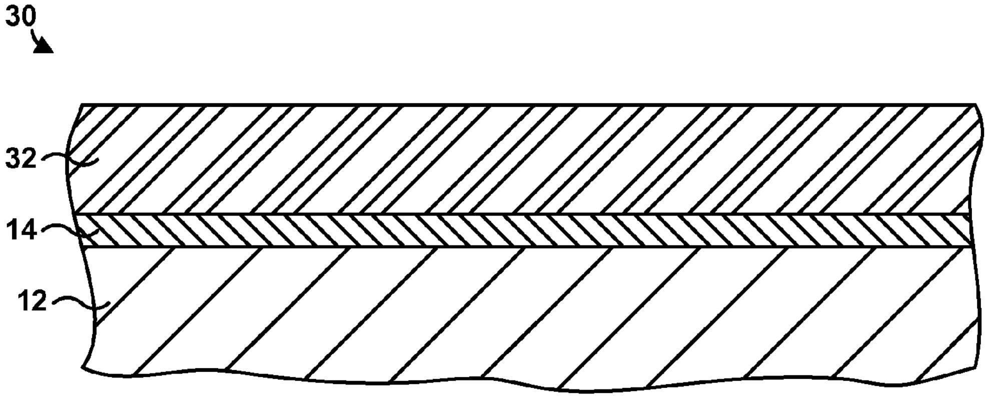


FIG. 3

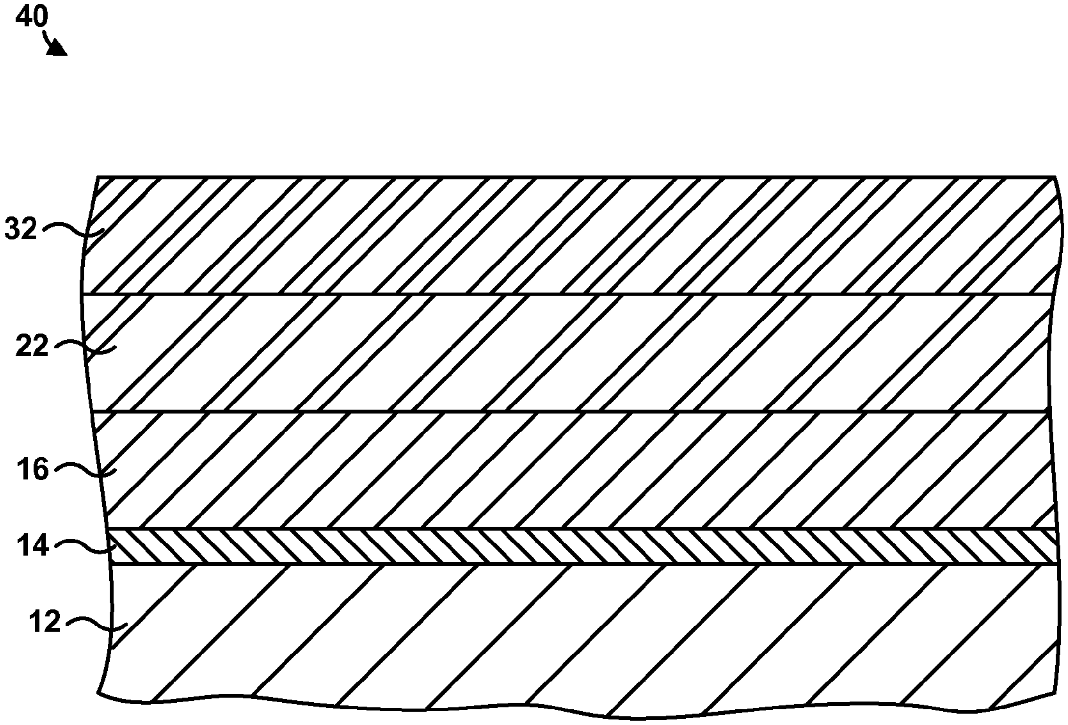


FIG. 4

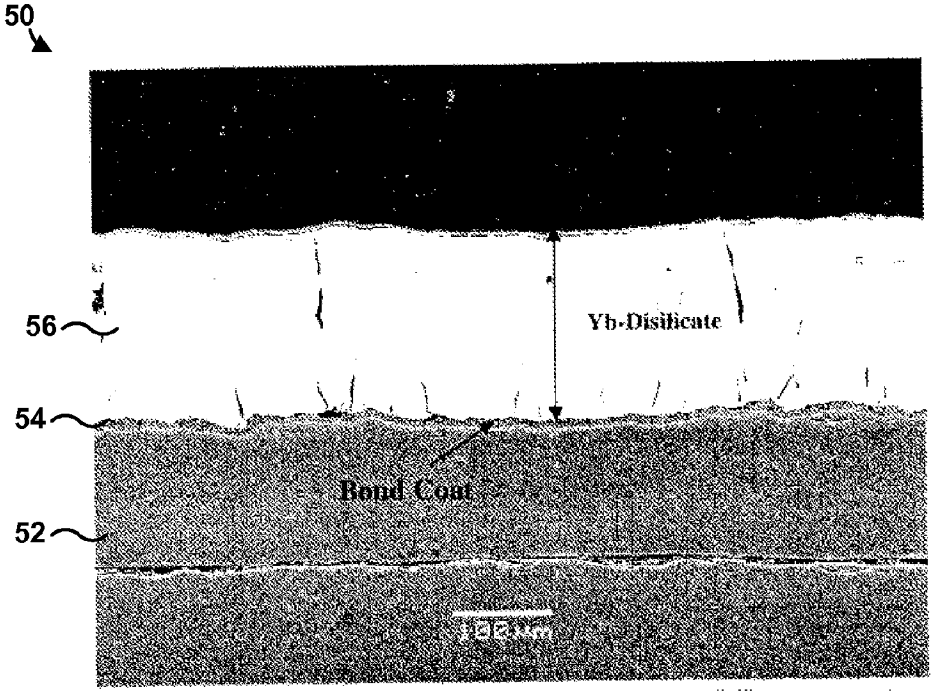

50
56
54
52
Yb-Disilicate
Bond Coat
100 µm

FIG. 5

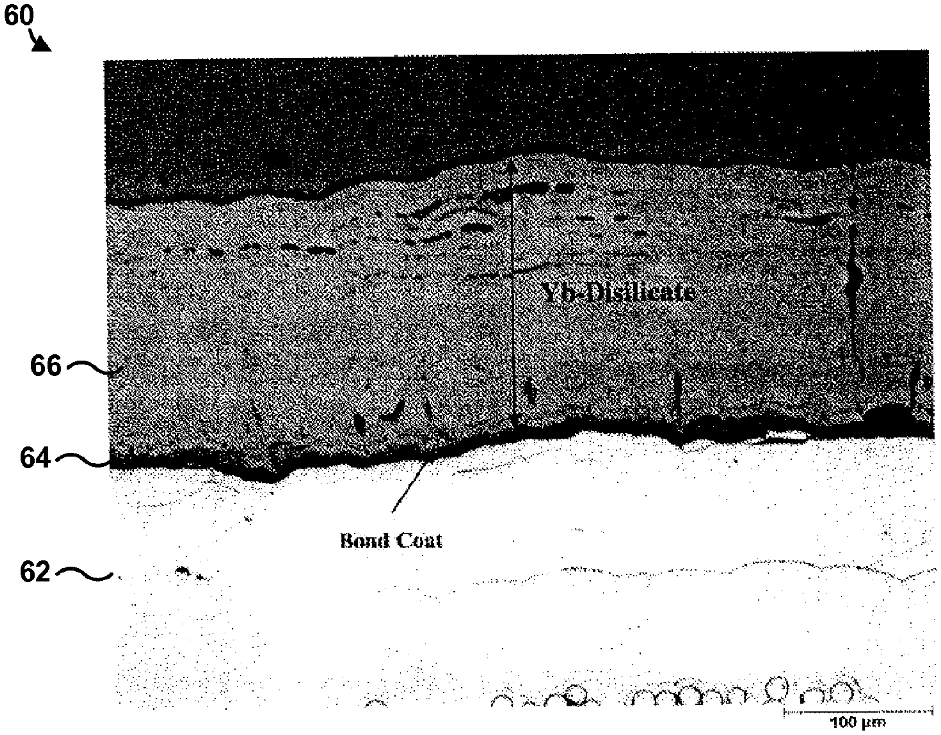

60
66
64
62
Yb-Disilicate
Bond Coat
100 µm

FIG. 6

BOND LAYERS FOR CERAMIC OR CERAMIC MATRIX COMPOSITE SUBSTRATES

TECHNICAL FIELD

[0001] The disclosure relates to bond layers for ceramic or ceramic matrix composite substrates.

BACKGROUND

[0002] Components of high-temperature mechanical systems, such as, for example, gas-turbine engines, must operate in severe environments. For example, the high-pressure turbine blades and vanes exposed to hot gases in commercial aeronautical engines typically experience metal surface temperatures of about 1000° C., with short-term peaks as high as 1100° C. Typical components of high-temperature mechanical systems include a Ni or Co-based superalloy substrate.

[0003] Economic and environmental concerns, i.e., the desire for improved efficiency and reduced emissions, continue to drive the development of advanced gas turbine engines with higher inlet temperatures. Some components of high-temperature mechanical systems include a ceramic or ceramic matrix composite (CMC)-based substrate, which may allow an increased operating temperature compared to a component with a superalloy substrate. The CMC-based substrate can be coated with an environmental barrier coating (EBC) to reduce exposure of a surface of the substrate to environmental species, such as water vapor or oxygen. The EBC also may provide some thermal insulation to the CMC-based substrate. The EBC may include a ceramic topcoat, and may be bonded to the substrate by a bond layer.

SUMMARY

[0004] In general, the disclosure is directed to a bond layer for a ceramic or CMC-based substrate and articles including a substrate and a bond layer. In accordance with some aspects of the disclosure, the bond layer may be capable of use at temperatures above the upper use temperature of a silicon (Si) bond layer, which may be about 1350° C. In this way, a bond layer formed in accordance with aspects of this disclosure may facilitate use of an article including such a bond layer at higher temperatures than an article that includes a Si bond layer.

[0005] In some examples, the bond layer may include a substantially homogenous mixture of Si and at least one of silica (SiO_2), alumina (Al_2O_3), zirconia (ZrO_2), a rare earth oxide (RE_2O_3, where RE is a rare earth element: La, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y, or Sc), zirconium silicate ($ZrSiO_4$), titanium oxide (TiO_2), tantalum oxide (Ta_2O_5), boron oxide (B_2O_3), an alkali metal oxide (Li_2O, Na_2O, K_2O, Rb_2O, Cs_2O, or Fr_2O), or an alkali earth metal oxide (BeO, MgO, CaO, SrO, BaO, or RaO). In other examples, the bond layer may include Si, an alkali metal oxide, and at least one of SiO_2, Al_2O_3, ZrO_2, hafnia (HfO_2), a rare earth oxide, $ZrSiO_4$, hafnium silicate ($HfSiO_4$), TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide. In other examples, the bond layer may include B_2O_3.

[0006] In one aspect, the disclosure is directed to an article that includes a substrate comprising a ceramic, a CMC, or a metal alloy including Si, and a bond layer formed on the substrate. In accordance with this aspect of the disclosure, the bond layer includes a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide. The article also may include at least one of a thermal barrier coating (TBC), an environmental barrier coating (EBC), or a calcia-magnesia-alumina-silicate (CMAS)-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

[0007] In another aspect, the disclosure is directed to an article that includes a substrate comprising a ceramic, a CMC, or a metal alloy including Si, and a bond layer formed on the substrate. In accordance with this aspect of the disclosure, the bond layer includes Si; an alkali metal oxide; and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide. The article also may include at least one of a TBC, an EBC, or a CMAS-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

[0008] In an additional aspect, the disclosure is directed to an article that includes a substrate comprising a ceramic, a CMC, or a metal alloy including Si, and a bond layer formed on the substrate. In accordance with this aspect of the disclosure, the bond layer includes B_2O_3. The article also may include at least one of a TBC, an EBC, or a CMAS-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

[0009] In a further aspect, the disclosure is directed to a method that includes forming a bond layer on a substrate comprising a ceramic, a CMC, or a metal alloy including Si. In accordance with this aspect of the disclosure, the bond layer includes a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide.

[0010] In another aspect, the disclosure is directed to a method that includes forming a bond layer on a substrate comprising a ceramic, a CMC or a metal alloy including Si. In accordance with this aspect of the disclosure, the bond layer includes Si; an alkali metal oxide; and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide.

[0011] In another aspect, the disclosure is directed to a method that includes forming a bond layer on a substrate comprising a ceramic, a CMC, or a metal alloy including Si. In accordance with this aspect of the disclosure, the bond layer includes B_2O_3.

[0012] The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the disclosure will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

[0013] FIG. **1** is a conceptual cross-sectional diagram that illustrates an example of an article that includes a bond layer formed on a substrate and an EBC formed on the bond layer.

[0014] FIG. **2** is a conceptual cross-sectional diagram that illustrates an example of an article that includes a bond layer formed on a substrate and a TBC formed on the bond layer.

[0015] FIG. **3** is a conceptual cross-sectional diagram that illustrates an example of an article that includes a bond layer formed on a substrate and a calcia-magnesia-alumina-silicate (CMAS)-resistant layer formed on the bond layer.

[0016] FIG. **4** is a conceptual cross-sectional diagram that illustrates an example of an article that includes a bond layer formed on a substrate, an EBC formed on the bond layer, a TBC formed on the EBC, and a CMAS-resistant layer formed on the TBC.

[0017] FIG. **5** is a cross-sectional micrograph of an example article that includes a bond layer formed in accordance with the aspects of the disclosure.

[0018] FIG. **6** is a cross-sectional micrograph of an example article **50** that includes a bond layer formed in accordance with the aspects of the disclosure.

DETAILED DESCRIPTION

[0019] In general, the disclosure is directed to a bond layer for a ceramic or CMC-based substrate and articles including a substrate and a bond layer. In accordance with some aspects of the disclosure, the bond layer may be capable of use at temperatures above the upper use temperature of a Si bond layer. Although the melting point of pure Si is about 1410° C., the melting temperature may decrease as Si is contaminated by impurities. In some examples, impurities may enter the Si bond layer during formation or use of the article. Because of the lower melting temperature, an upper use temperature of an article that includes a Si bond layer may be limited to about 1350° C. in some examples.

[0020] In some implementations in which the substrate of the article includes a ceramic or CMC, the ceramic or CMC substrate may be able to withstand use temperatures of greater than 1350° C. or even greater than 1410° C. For example, some advanced CMCs, such as those in which silicon is not included in the matrix material, may be able to withstand use temperatures of up to about 1482° C. (about 2700° F.). Accordingly, in examples in which an article includes a bond layer of Si, the bond layer may limit the upper use temperature to below a temperature which the substrate is capable of withstanding.

[0021] In some examples, the bond layer compositions of the present disclosure may be able to withstand temperatures greater than about 1350° C. or greater than about 1410° C. The bond layer compositions of the present disclosure may thus facilitate use of an article including the bond layer compositions at temperatures greater than about 1350° C. or greater than about 1410° C. The bond layer compositions of the present disclosure may also provide adherence between the substrate, the bond layer, and a layer formed on the bond layer.

[0022] FIG. **1** is a conceptual cross-sectional diagram that illustrates an example of an article **10** that includes a bond layer **14** formed on a substrate **12** and an EBC **16** formed on bond layer **14**. Article **10** is a component of a high temperature mechanical system, such as, for example, a gas turbine engine or the like. For example, article **10** may be a turbine blade, a turbine vane, a turbine blade track, or a combustor liner.

[0023] Substrate **12** may include a metal alloy that includes silicon, a ceramic, or a CMC. In examples in which substrate **12** includes a ceramic, the ceramic may be substantially homogeneous. In some examples, a substrate **12** that includes a ceramic includes, for example, a Si-containing ceramic, such SiO_2, silicon carbide (SiC) or silicon nitride (Si_3N_4); Al_2O_3; aluminosilicate (e.g., Al_2SiO_5); or the like. In other examples, substrate **12** includes a metal alloy that includes Si, such as a molybdenum-silicon alloy (e.g., $MoSi_2$) or a niobium-silicon alloy (e.g., $NbSi_2$).

[0024] In examples in which substrate **12** includes a CMC, substrate **12** includes a matrix material and a reinforcement material. The matrix material includes a ceramic material, such as, for example, SiC, Si_3N_4, Al_2O_3, aluminosilicate, SiO_2, or the like. The CMC further includes a continuous or discontinuous reinforcement material. For example, the reinforcement material may include discontinuous whiskers, platelets, or particulates. As other examples, the reinforcement material may include a continuous monofilament or multifilament weave.

[0025] The composition, shape, size, and the like of the reinforcement material may be selected to provide the desired properties to the substrate **12** including the CMC. In some examples, the reinforcement material is chosen to increase the toughness of a brittle matrix material. The reinforcement material may additionally or alternatively be chosen to modify a thermal conductivity, electrical conductivity, thermal expansion coefficient, hardness, or the like of a substrate **12** including a CMC.

[0026] In some examples, the composition of the reinforcement material is the same as the composition of the matrix material. For example, a matrix material comprising SiC may surround a reinforcement material comprising SiC whiskers. In other examples, the reinforcement material includes a different composition than the composition of the matrix material, such as aluminosilicate fibers in an Al_2O_3 matrix, or the like. One composition of a substrate **12** that comprises a CMC includes a reinforcement material comprising SiC continuous fibers embedded in a matrix material comprising SiC.

[0027] Some example CMCs used for substrate **12** include composites of SiC or Si_3N_4 and silicon oxynitride (Si_2N_2O) or silicon aluminum oxynitride, and oxide-oxide ceramics, such as a matrix material of Al_2O_3 or aluminosilicate and a reinforcement material comprising NEXTEL™ Ceramic Oxide Fiber 720 (available from 3M Co., St. Paul, Minn.).

[0028] Bond layer **14** is formed directly on substrate **12**, and includes a composition that provides adherence between substrate **12** and a layer formed on bond layer **14**, such as EBC **16**. In some examples, the adherence provided by bond layer **14** between substrate **12** and EBC **16** may be greater than the adherence between substrate **12** and EBC **16**, without bond layer **14**.

[0029] As described above, bond layer **14** may include a composition that may be stable at temperatures above 1350° C. and/or above about 1410° C. In this way, bond layer **14** may allow use of article **10** at temperatures which lead to temperatures of bond layer **14** above 1350° C. and/or above about 1410° C. In some examples, article **10** may be used in a environment in which ambient temperature is greater than the temperature at which bond layer **14** is stable, e.g., because bond layer **14** may be coated with at least one layer, such as EBC **16** and/or TBC **22** (FIG. **2**), that provides thermal insulation to bond layer **14** and reduces the temperature experienced by bond layer **14** compared to the ambient temperature or the surface temperature of the layer(s) formed on bond layer **14**, e.g., EBC **16**.

[0030] In some examples, bond layer **14** may include or consist essentially of a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide. As used herein, the term “substantially homogenous mixture" includes a mixture that consists of substantially a single phase, i.e., discrete phases of distinct composition are substantially not present in the mixture or in a layer formed by the mixture. For example, a layer including a substantially homogenous mixture may include a second phase that is present in an amount of less than 1 volume percent (vol. %). Also, as used herein, "consist essentially of" means that the composition includes the listed components, may include additional components that do not materially affect the basic properties of the composition, and may not include additional components that materially affect the basic properties of the composition.

[0031] In some examples, the presence of Si in bond layer **14** may promote adherence between bond layer **14** and substrate **12**, such as, for example, when substrate **12** includes Si or a compound containing Si. The addition of an oxide or silicate to bond layer **14** may contribute to bond layer **14** being stable at temperatures above 1350° C. and/or about 1410° C.

[0032] In some examples, bond layer **14** may include or consist essentially of up to 99 weight percent (wt. %) Si and a balance of the at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %. In other examples, bond layer **14** may include or consist essentially of up to about 50 wt. % Si and a balance of the at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

[0033] In some implementations, bond layer **14** may include or consist essentially of a substantially homogenous mixture of silicon, at least one of SiO_2, Al_2O_3, ZrO_2, or a rare earth oxide, and at least one of $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide. In some such examples, bond layer **14** may include or consist essentially of up to about 99 wt. % Si, up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, or a rare earth oxide, and up to about 50 wt. % of the at least one of $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %. In other examples, bond layer **14** may include or consist essentially of up to about 50 wt. % Si, up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, or a rare earth oxide, and up to about 20 wt. % of the at least one of $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

[0034] In other examples, bond layer **14** may include or consist essentially of Si, an alkali metal oxide, and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide. In some examples in which bond layer **14** includes or consists essentially of such a composition, bond layer **14** may include or consist essentially of a substantially homogeneous mixture. In other examples in which bond layer **14** includes or consists essentially of such a composition, bond layer **14** may include two or more discrete phases, e.g., a Si phase and an oxide phase.

[0035] In some implementations in which bond layer **14** includes or consists essentially of Si, an alkali metal oxide, and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, bond layer **14** may include or consist essentially of up to about 99 wt. % Si, up to about 50 wt. % of the alkali metal oxide, and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %. In other implementations, bond layer **14** may include or consist essentially of up to about 50 wt. % Si, up to about 20 wt. % of the alkali metal oxide, and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %.

[0036] In some examples, bond layer **14** may include or consist essentially of Si, an alkali metal oxide, at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide. In some implementations, bond layer **14** may include or consist essentially of up to about 99 wt. % Si, up to about 50 wt. % of the alkali metal oxide, and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and up to about 50 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %. In other implementations, bond layer **14** may include or consist essentially of up to about 50 wt. % Si, up to about 20 wt. % of the alkali metal oxide, and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and up to about 20 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %.

[0037] In other examples, bond layer **14** may include or consist essentially of B_2O_3. In some examples, in addition to B_2O_3, bond layer **14** may include or consist essentially of at least one of Si, SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide. In some examples, bond layer **14** may include or consist essentially of up to about 50 wt. % B_2O_3 and a balance of the at least one of Si, SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %. In other examples, bond layer **14** may include or consist essentially of up to about 20 wt. % B_2O_3 and a balance of the at least one of Si, SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

[0038] In some examples, bond layer **14** may include or consist essentially of B_2O_3, Si, at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide. In some implementations, bond layer **14** may include or consist essentially of up to about 50 wt. % B_2O_3, up to about 99 wt. % Si, up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and up to about 50 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %. In other implementations, bond layer **14** may include or consist essentially of up to about 20 wt. % B_2O_3, up to about 50 wt. % Si, up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide, and up to about 20 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

[0039] Regardless of the composition of bond layer **14**, bond layer **14** may have a thickness of less than about 200 micrometers (μm; about 0.007874 inch). In some examples, bond layer **14** may include a thickness of up to about 50 μm (about 0.001969 inch), up to about 25 μm (about 0.0009843 inch), or between about 1 μm (about 0.00003937 inch) and about 25 μm (about 0.0009843 inch). In some examples, a bond layer **14** may be thinner when bond layer **14** includes a greater amount of Si and thicker when bond layer **14** includes a lesser amount of Si.

[0040] Bond layer **14** may be formed on substrate **12** using, for example, plasma spraying, physical vapor deposition (PVD), electron beam physical vapor deposition (EB-PVD), directed vapor deposition (DVD), chemical vapor deposition (CVD), cathodic arc deposition slurry process deposition, sol-gel process deposition, or electrophoretic deposition.

[0041] In some examples in which bond layer **14** includes at least two components (e.g., Si and at least one other component), the at least two components may be co-deposited. Alternatively, in examples in which bond layer **14** includes at least two components, at least one of the at least two components may be deposited in a separate layer from at least one other of the at least two components. For example, when bond layer **14** includes Si and at least one oxide or $ZrSiO_4$ (referred to hereafter as oxide for brevity), Si may be deposited in a separate layer from the oxide. As examples, Si and oxide may be deposited on substrate **12** in the following orders: Si/O; O/Si; Si/O/Si/O; O/Si/O/Si. Of course, the deposition process is not limited to two or fewer Si layers and/or two or fewer oxide layers, and as many alternating layers of Si and oxide may be deposited as desired.

[0042] In some examples in which bond layer **14** includes at least two oxides (and/or $ZrSiO_4$), at least one of the at least two oxides may be deposited in a separate layer from at least one other of the at least two oxides. In some implementations, at least one of the at least two oxides may be co-deposited with Si, while at least one other oxide may be deposited in a separate layer. In other implementations, Si, at least one of the at least two oxides, and at least another of the at least two oxides may be deposited in three or more separate layers. To summarize, the components of bond layer **14** may be deposited in any combination of separately deposited layers and/or co-deposited layers.

[0043] As described above, in some examples, bond layer **14** may include or consist essentially of a substantially homogenous mixture. In some examples, bond layer **14** is deposited as a substantially homogeneous layer, e.g., when bond layer **14** includes at least two components, the at least two components may be co-deposited as a substantially homogenous layer. In other examples, such as when bond layer **14** is deposited as multiple layers having different compositions, bond layer **14** may undergo a post-deposition heat treatment to form the substantially homogenous layer.

[0044] For example bond layer **14** may be exposed to a post-deposition heat treatment at a temperature up to the temperature capability of substrate **12**, which may be, for example, up to about 1500° C. for some substrates **12** that include a CMC. In some examples, the post-deposition heat treatment temperature may be between about 1350° C. and about the temperature capability of substrate **12** (e.g., about 1500° C.). Bond layer **14** may be exposed to the heat treatment for up to about 10 hours, such as between about 10 minutes and about 1 hour. The heat treatment may be performed in an oxidizing atmosphere, such as air; a reducing atmosphere, such as hydrogen; or an inert atmosphere, such as argon, helium, or nitrogen. In some examples, bond layer **14** may undergo the heat treatment after deposition of bond layer **14** on substrate **12** and before deposition of an overlayer such as EBC **16**. In other examples, bond layer **14** may undergo the heat treatment after deposition of bond layer **14** on substrate **12** and after deposition of an overlayer such as EBC **16**.

[0045] While the post-deposition heat treatment may in some implementations be used to create a substantially homogenous mixture in bond layer **14**, post-deposition heat treatment may also cause chemical reactions among components of bond layer **14** and/or between components of bond layer **14** and components of substrate **12** and/or between components of bond layer **14** and components of an overlayer, such as EBC **16**. This may contribute to adherence between substrate **12** and bond layer **14** and/or between bond layer **14** and an overlayer, such as EBC **16**. Accordingly, bond layer **14** may or may not undergo heat treatment in examples in which bond layer **14** does not include a substantially homogenous mixture and/or in examples in which bond layer **14** is deposited as a substantially homogenous mixture. Hence, regardless of the composition, phase constitution, and/or deposition process used to form bond layer **14**, layer **14** may or may not be exposed to a post-deposition heat treatment.

[0046] EBC **16** is formed on bond layer **14**. EBC **16** may reduce or substantially prevent attack of bond layer **14** and/or substrate **12** by chemical species present in the environment in which article **10** is utilized, e.g., in the intake gas or exhaust gas of a gas turbine engine. For example, EBC **16** may include a material that is resistant to oxidation or water vapor attack. Exemplary materials for use in EBC **16** include mullite; glass ceramics such as barium strontium aluminosilicate ($BaO—SrO—Al_2O_3\text{-}2SiO_2$; BSAS), calcium aluminosilicate ($CaAl_2Si_2O_8$; CAS), cordierite (magnesium aluminosilicate), and lithium aluminosilicate; and rare earth silicates (silicates of Lu, Yb, Tm, Er, Ho, Dy, Tb, Gd, Eu, Sm, Pm, Nd, Pr, Ce, La, Y, or Sc). The rare earth silicate may be a rare earth mono-silicate (RE_2SiO_5, where RE stands for "rare earth") or a rare earth di-silicate ($RE_2Si_2O_7$, where RE stands for "rare earth"). In some examples, EBC **16** is formed as a substantially non-porous layer, while in other examples, EBC **16** is formed as a layer that includes a plurality of cracks. EBC **16** may be formed using, for example, CVD; PVD, including EB-PVD and DVD; plasma spraying or another thermal spraying process, or the like. In some examples, EBC **16** may comprise a thickness between about 0.001 inch and about 0.1 inch. EBC **16** may be formed on bond layer **14** prior to exposing bond layer **14** to a heat treatment or after exposing bond layer **14** to a heat treatment, as described above. In some examples, EBC **16** may comprise a thickness between about 0.003 inch (about 76.2 μm) and about 0.05 inch (about 1270 μm).

[0047] In some examples, an article may include a layer other than EBC **16** formed on bond layer **14**. FIG. **2** is a conceptual cross-sectional diagram that illustrates an example of an article **20** that includes bond layer **14** formed on substrate **12** and a TBC **22** formed on bond layer **14**. TBC **22** includes a thermally insulative material. Common TBCs include ceramic layers comprising ZrO_2 or HfO_2. A TBC **22** that includes ZrO_2 or HfO_2 optionally may include one or more other elements or compounds to modify a desired characteristic of the TBC **22**, such as, for example, phase stability, thermal conductivity, or the like. Exemplary additive elements or compounds include rare earth oxides (oxides of Lu, Yb, Tm, Er, Ho, Dy, Tb, Gd, Eu, Sm, Pm, Nd, Pr, Ce, La, Y, or Sc). Particular examples of materials from which TBC **22** may be formed include ZrO_2 stabilized with between 7 weight percent (wt. %) and 8 wt. % Y_2O_3; ZrO_2 stabilized with Yb_2O_3, Sm_2O_3, and at least one of Lu_2O_3, Sc_2O_3, Ce_2O_3, Gd_2O_3, Nd_2O_3, or Eu_2O_3; or HfO_2 stabilized with Yb_2O_3, Sm_2O_3, and at least one of Lu_2O_3, Sc_2O_3, Ce_2O_3, Gd_2O_3, Nd_2O_3, or Eu_2O_3. In some examples, TBC **22** may include ZrO_2 and/or HfO_2 in combination with additive elements or compounds such that at least some of the stabilized ZrO_2 and/or HfO_2 forms a metastable tetragonal-prime crystalline phase, a cubic crystalline phase, or a compound phase ($RE_2Zr_2O_7$ or $RE_2Hf_2O_7$, where RE is a rare earth element).

[0048] In some examples, TBC **22** includes ZrO_2 and/or HfO_2, a primary dopant, a first co-dopant, and a second co-dopant. The primary dopant is preferably present in a greater amount than either the first or second co-dopants, and may be present in an amount less than, equal to, or greater than the total amount of the first and second co-dopants. The primary dopant includes Yb_2O_3, the first co-dopant includes Sm_2O_3, and the second co-dopant includes at least one of Lu_2O_3, Sc_2O_3, Ce_2O_3, Gd_2O_3, Nd_2O_3, or Eu_2O_3.

[0049] In some examples, TBC **22** includes between about 2 mol. % and about 40 mol. % of the primary dopant. In other examples, TBC **22** includes between approximately 2 mol. % and approximately 20 mol. % of the primary dopant or between approximately 2 mol. % and approximately 10 mol. % of the primary dopant.

[0050] In some examples, TBC **22** includes between about 0.1 mol. % and about 20 mol. % of the first co-dopant. In other examples, TBC **22** includes between about 0.5 mol. % and about 10 mol. % of the first co-dopant or between about 0.5 mol. % and about 5 mol. % of the first co-dopant.

[0051] In some examples, TBC **22** includes between about 0.1 mol. % and about 20 mol. % of the second co-dopant. In other examples, TBC **22** includes between about 0.5 mol. % and about 10 mol. % of the second co-dopant or between about 0.5 mol. % and about 5 mol. % of the second co-dopant.

[0052] In some examples, the composition of TBC **22** provides a desired phase constitution. For a first barrier coating layer **18** including ZrO_2 and/or HfO_2, a primary dopant, a first co-dopant, and a second co-dopant, accessible phase constitutions include metastable tetragonal-prime, cubic, and compound ($RE_2Zr_2O_7$ and $RE_2Hf_2O_7$, where RE is a rare earth element). To achieve a RE_2O_3—ZrO_2 (and/or HfO_2) compound phase constitution, TBC **22** includes between about 20 mol. % and about 40 mol. % primary dopant, between about 10 mol. % and about 20 mol. % first co-dopant, between about 10 mol. % and about 20 mol. % second co-dopant, and the balance base oxide (ZrO_2 and/or HfO_2) and any impurities present. To achieve a cubic phase constitution, TBC **22** includes between about 5 mol. % and about 20 mol. % primary dopant, between about 2 mol. % and about 10 mol. % first co-dopant, between about 2 mol. % and about 10 mol. % second co-dopant, and a balance base oxide (ZrO_2 and/or HfO_2) and any impurities present. In some examples, to achieve a metastable tetragonal phase constitution, TBC **22** includes between about 2 mol. % and about 5 mol. % primary dopant, between about 0.5 mol. % and about 3 mol. % first co-dopant, between about 0.5 mol. % and about 3 mol. % second co-dopant, and a balance base oxide and any impurities present.

[0053] TBC **22** may be formed on bond layer **14** as a porous layer or a columnar layer, and may be formed using, for example, CVD; PVD, including EB-PVD and DVD; plasma spraying or another thermal spraying process, or the like.

[0054] In some examples, an article may include a layer other than EBC **16** or TBC **22** formed on bond layer **14**. FIG. **3** is a conceptual cross-sectional diagram that illustrates an example of an article **30** that includes bond layer **14** formed on substrate **12** and a CMAS-resistant layer **32** formed on bond layer **14**. CMAS-resistant layer **32** includes an element or compound that reacts with CMAS to form a solid or a highly-viscous reaction product (i.e., a reaction product that is a solid or highly viscous at the temperatures experienced by article **30**). In some examples, CMAS-resistant layer **32** includes Al_2O_3 and at least one rare earth oxide, such as, for example, an oxide of at least one of Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and combinations thereof. The combination of Al_2O_3 and at least one rare earth oxide may allow tailoring of one or more properties of CMAS-resistant layer **32**, such as, for example, the chemical reactivity of CMAS-resistant layer **32** with CMAS, the viscosity of the reaction products, the coefficient of thermal expansion (CTE) of CMAS-resistant layer **32**, the chemical compatibility of CMAS-resistant layer **32** with bond layer **14**, or the like.

[0055] In some examples, CMAS-resistant layer **32** is essentially free of ZrO_2 and/or HfO_2. That is, in these examples, CMAS-resistant layer **32** includes at most trace amounts of ZrO_2 and/or HfO_2, such as, for example, the amounts present in commercially-available rare earth oxides.

[0056] In some examples, CMAS-resistant layer **32** includes SiO_2 in addition to the Al_2O_3 and at least one rare earth oxide. SiO_2 can be added to CMAS-resistant layer **32** to allow further manipulation of the properties of CMAS-resistant layer **32**, such as, for example, the chemical reactivity, viscosity of the reaction products, the CTE, the chemical compatibility of CMAS-resistant layer **32** with bond layer **14**, or the like.

[0057] In some examples, CMAS-resistant layer **32** optionally includes other additive components, such as, for example, TiO_2, Ta_2O_5, $HfSiO_4$, alkali metal oxides, alkali earth metal oxides, or mixtures thereof. The additive components may be added to CMAS-resistant layer **32** to modify one or more desired properties of CMAS-resistant layer **32**. For example, the additive components may increase or decrease the reaction rate of CMAS-resistant layer **32** with CMAS, may modify the viscosity of the reaction product from the reaction of CMAS and CMAS-resistant layer **32**, may increase adhesion of the CMAS-resistant layer **32** to bond layer **14**, may increase or decrease the chemical stability of CMAS-resistant layer **32**, or the like.

[0058] CMAS-resistant layer **32** may include up to about 99 mol. % of the at least one rare earth oxide, ±1 mol. %, and up to about 90 mol. % of Al_2O_3, with a total of 100 mol. %. In some examples, CMAS-resistant layer **32** may also include up to about 90 mol. % of SiO_2. In some examples, CMAS-resistant layer **32** may additionally include up to about 50 mol. % of at least one of TiO_2, Ta_2O_5, $HfSiO_4$, an alkali oxide, or an alkali earth oxide.

[0059] In some examples, CMAS-resistant layer **32** includes between about 20 mol. % and about 80 mol. % of at least one rare earth oxide, between about 5 mol. % and about 50 mol. % Al_2O_3, and, optionally, between about 5 mol. % to about 50 mol. % of SiO_2. In some examples, CMAS-resistant layer **32** may additionally include between about 0.1 mol. % and about 30 mol. % of at least one of TiO_2, Ta_2O_5, $HfSiO_4$, an alkali oxide, or an alkali earth oxide.

[0060] As described above, CMAS-resistant layer **32** reacts with CMAS that reaches layer **32** to form a solid or highly viscous reaction product. The reaction product may have a melting temperature significantly higher than CMAS (e.g., higher than about 1200-1250° C.). A solid or highly viscous reaction product is desired because the CMAS-resistant layer **32** is consumed as it reacts with CMAS. If, for example, the reaction product of CMAS-resistant layer **32** and CMAS was a relatively low viscosity liquid, the low viscosity liquid would contact bond layer **14** and/or substrate **12** once the CMAS-resistant layer **32** is consumed by the reaction, which is the very occurrence the CMAS-resistant layer **32** is designed to prevent.

[0061] If the reaction product is a solid or highly viscous, however, a reaction layer will form on the surface of CMAS-resistant layer **32**, which will lower the reaction rate of the CMAS with CMAS-resistant layer **32**. That is, once a solid or highly viscous reaction layer forms on the surface of CMAS-resistant layer **32**, the reaction between CMAS-resistant layer **32** and CMAS will slow, because any further reaction will require the diffusion of CMAS through the reaction layer to encounter the CMAS-resistant layer **32**, or diffusion of a component of CMAS-resistant layer **32** through the reaction layer to encounter the CMAS. In either case, the diffusion of either CMAS or the component of CMAS-resistant layer **32** is expected to be the limiting step in the reaction once a solid or highly viscous reaction layer is formed on the surface of CMAS-resistant layer **32**, because diffusion will be the slowest process.

[0062] Although EBC **16**, TBC **22**, and CMAS-resistant layer **32** have been described is separate examples as being formed on bond layer **14**, in some examples, at least two of EBC **16**, TBC **22**, and CMAS-resistant layer **32** may be formed over bond layer **14**. FIG. **4** is a conceptual cross-sectional diagram that illustrates an example of an article **40** that includes bond layer **14** formed on substrate **12**, EBC **16** formed on bond layer **14**, TBC **22** formed on EBC **16**, and CMAS-resistant layer **32** formed on TBC **22**. As used herein, "formed over" means a layer or coating that is formed on top of another layer or coating, and encompasses both a first layer or coating formed immediately adjacent a second layer or coating and a first layer or coating formed on top of a second layer or coating with one or more intermediate layer or coating present between the first and second layers or coatings. In contrast, "formed directly on" and "formed on" denote a layer or coating that is formed immediately adjacent another layer or coating, i.e., there are no intermediate layers or coatings.

[0063] Although FIG. **4** illustrates an article **40** that includes EBC **16**, TBC **22**, and CMAS-resistant layer **32**, in other examples, an article may include two of these layers. For example, an article may include substrate **12**, bond layer **14** formed on substrate **12**, EBC **16** formed over bond layer **14**, and TBC **22** formed over EBC **16**. As another example, an article may include substrate **12**, bond layer **14** formed on substrate **12**, TBC **22** formed over bond layer **14**, and CMAS-resistant layer **32** formed over TBC **22**.

[0064] Additionally, while CMAS-resistant layer **32** is formed over TBC **22**, which is formed over EBC **16** in FIG. **4**, other configurations of layers are possible. For example, TBC **22** may be formed over CMAS-resistant layer **32** and/or EBC **16** may be formed over TBC **22**. Other configurations and combinations of layers will be apparent to those of ordinary skill in the art, and fall within the scope of the disclosure and the following claims.

EXAMPLES

Example 1

[0065] FIG. **5** is a cross-sectional micrograph of an example article **50** that includes a bond layer formed in accordance with the aspects of the disclosure. Article **50** includes a substrate **52** that includes a SiC matrix reinforced with SiC fibers, a bond layer **54** that includes Si, SiO_2, Yb_2O_3, and ZrO_2, and an EBC **56** that includes $Yb_2Si_2O_7$ (ytterbium disilicate). The components of bond layer **54** were co-deposited in a single layer on substrate **52** using DVD, and EBC **56** was deposited using DVD on bond layer **54** prior to exposing bond layer **54** to heat treatment. Article **50** was then exposed to heat treatment in air at about 1410° C. for about 1 hour prior to testing.

[0066] Article **50** was then exposed to 100 hour thermal cycling with 1 hour cycles in 90% H_2O and 10% O_2 atmosphere at about 1430° C. (above the melting temperature of pure silicon). FIG. **5** illustrates a portion of article **50** after completion of the thermal cycling testing. FIG. **5** illustrates that EBC **56** maintained good adherence to bond layer **54** and substrate **52** after the thermal cycling.

Example 2

[0067] FIG. **6** is a cross-sectional micrograph of an example article **60** that includes a bond layer formed in accordance with the aspects of the disclosure. Article **60** includes a substrate **62** that includes a SiC matrix reinforced with SiC fibers, a bond layer **64** that includes Si, SiO_2, Yb_2O_3, and ZrO_2, and an EBC **66** that includes $Yb_2Si_2O_7$ (ytterbium disilicate). The components of bond layer **64** were co-deposited in a single layer on substrate **62** using DVD, and EBC **66** was deposited using DVD on bond layer **64** prior to exposing bond layer **64** to heat treatment. Article **50** was then exposed to heat treatment in air at about 1430° C. for about 1 hour prior to testing.

[0068] Article **60** was then exposed to 100 hour thermal cycling with 1 hour cycles in 90% H_2O and 10% O_2 atmosphere at about 1450° C. (above the melting temperature of pure silicon). FIG. **6** illustrates a portion article **60** after completion of the thermal cycling testing. FIG. **6** illustrates that EBC **66** maintained good adherence to bond layer **64** and substrate **62** after the thermal cycling.

[0069] Various examples have been described. These and other examples are within the scope of the following claims.

1. An article comprising:

a substrate comprising a ceramic, a ceramic matrix composite (CMC), or a metal alloy that includes Si;

a bond layer formed on the substrate, wherein the bond layer comprises a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide; and

at least one of a thermal barrier coating (TBC), an environmental barrier coating (EBC), or a calcia-magnesia-alumina-silicate (CMAS)-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

2. The article of claim **1**, wherein the bond layer consists essentially of the substantially homogeneous mixture of Si and at the least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide.

3. (canceled)

4. The article of claim **1**, wherein the bond layer comprises a substantially homogeneous mixture of Si; at least one of SiO_2, Al_2O_3, ZrO_2, or a rare earth oxide; and at least one of $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide.

5. (canceled)

6. The article of claim **4**, wherein the bond layer comprises up to about 50 wt. % Si, up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, or a rare earth oxide, and up to about 20 wt. % of the at least one of $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

7. (canceled)

8. The article of claim **1**, wherein

the bond layer comprises a substantially homogeneous mixture of Si; the alkali metal oxide; and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or these alkali earth metal oxide.

9. The article of claim **8**, wherein consists essentially of Si; the alkali metal oxide; and the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide.

10. (canceled)

11. The article of claim **8**, wherein the bond layer comprises up to about 50 wt. % Si, up to about 20 wt. % of the alkali metal oxide, and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %.

12. The article of claim **8**, wherein the bond layer comprises Si; an alkali metal oxide; at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide; and at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide.

13. (canceled)

14. The article of claim **12**, wherein the bond layer comprises up to about 50 wt. % Si; up to about 20 wt. % of the alkali metal oxide; and up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide; and up to about 20 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide, with a total of 100 wt. %.

15. (canceled)

16. An article comprising:

a substrate comprising a ceramic, a ceramic matrix composite (CMC), or a metal alloy comprising Si; and

a bond layer formed on the substrate, wherein the bond layer comprises B_2O_3; and

at least one of a thermal barrier coating (TBC), an environmental barrier coating (EBC), or a calcia-magnesia-alumina-silicate (CMAS)-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

17. The article of claim **16**, wherein the bond layer consists essentially of B_2O_3.

18. (canceled)

19. The article of claim **16**, wherein the bond layer comprises up to about 20 wt. % B_2O_3 and a balance of the at least one of Si, SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

20. The article of claim **16**, wherein the bond layer further comprises Si; at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide; and at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide.

21. The article of claim **20**, wherein the bond layer comprises up to about 20 wt. % B_2O_3; up to about 50 wt. % Si; up to about 99 wt. % of the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, or a rare earth oxide; and up to about 20 wt. % of the at least one of $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, an alkali metal oxide, or an alkali earth metal oxide, with a total of 100 wt. %.

22. (canceled)

23. A method comprising:

forming a bond layer on a substrate comprising a ceramic, a ceramic matrix composite (CMC), or a metal alloy comprising Si, wherein the bond layer comprises a substantially homogeneous mixture of Si and at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide; and

forming at least one of a thermal barrier coating (TBC), an environmental barrier coating (EBC), or a calcia-magnesia-alumina-silicate (CMAS)-resistant layer formed on the bond layer, wherein the bond layer is configured to increase adhesion between the substrate and the at least one of the TBC, the EBC, or the CMAS-resistant layer.

24. The method of claim **23**, wherein forming the bond layer on the substrate comprises forming on the substrate a bond layer consisting essentially of the substantially homogeneous mixture of Si and the at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide.

25. (canceled)

26. The method of claim **23**, wherein forming the bond layer on the substrate comprises:

forming a first layer comprising Si over the substrate,

forming a second layer comprising the at least one of SiO_2, Al_2O_3, ZrO_2, a rare earth oxide, $ZrSiO_4$, TiO_2, Ta_2O_5, B_2O_3, an alkali metal oxide, or an alkali earth metal oxide over the substrate, and

wherein heat treating the bond layer comprises heat treating the first layer and the second layer at between about 1350° C. and about 1500° C. for up to about 10 hours to form the bond layer.

27. The method of claim **23**, wherein forming the bond layer on the substrate comprising the ceramic, the ceramic matrix composite (CMC), or the metal alloy comprising Si comprises:

forming a bond layer on the substrate comprising the ceramic, the ceramic matrix composite (CMC), or the metal alloy including Si, wherein the bond layer comprises a substantially homogeneous mixture of Si; an alkali metal oxide; and at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide.

28-29. (canceled)

30. The method of claim **27**, wherein forming the bond layer on the substrate comprises:

forming a first layer comprising Si over the substrate,

forming a second layer comprising the alkali metal oxide and the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide over the substrate, and

wherein heat treating the bond layer comprises heat treating the first layer and the second layer at between about 1350° C. and about 1500° C. for up to about 10 hours to form the layer.

31. The method of claim **27**, wherein forming the bond layer on the substrate comprises:

forming a first layer comprising Si over the substrate,

forming a second layer comprising the alkali metal oxide over the substrate,

forming a third layer comprising the at least one of SiO_2, Al_2O_3, ZrO_2, HfO_2, a rare earth oxide, $ZrSiO_4$, $HfSiO_4$, TiO_2, Ta_2O_5, B_2O_3, or an alkali earth metal oxide over the substrate, and

wherein heat treating the bond layer comprises heat treating the first layer, the second layer, and the third layer at between about 1350° C. and about 1500° C. for up to about 10 hours to form the bond layer.

32-36. (canceled)

* * * * *