ABSTRACT

A thin ceramic substrate having unusually high strength properties is manufactured by a casting process which produces a triple layered ceramic body. The exterior layers of the body having incorporated therein a grain growth inhibitor. The interior layer of the body has incorporated therein a grain growth promoter. Upon sintering, the composite body is defined by an interior grain size which is approximately twice as large as the exterior grain size.

15 Claims, 8 Drawing Figures
STRENGTHENING ALUMINA SUBSTRATES BY INCORPORATING GRAIN GROWTH INHIBITOR IN SURFACE AND PROMOTER IN INTERIOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to improving the strength properties of ceramic bodies, and is particularly concerned with enhancing the strength properties of thin, high-alumina ceramic substrates that are used in the electronics industry.

2. Discussion of the Prior Art

Ceramics have always played an important role in the electronics industry. Due to their well-known insulating properties, ceramics have enjoyed wide use as supporting bodies (commonly termed substrates) for many varied electrical circuits. With the recent developments in thin film, microelectronic circuits, attempts have been made to employ extremely thin ceramic bodies as substrates for the circuits. However, thin ceramic bodies are frequently subjected to fracture because of their brittleness. Furthermore, this fracture is initiated by a wide range of factors encountered in the manufacture and use of thin film circuits. For example, fracture frequently occurs in the handling and masking of the substrates, and in bonding the circuits to the substrates. The aforementioned bonding causes the substrates to fracture as a result of thermal shock; that is, the intense heat associated with the bonding is too much for the thin ceramics to withstand. Whatever its cause, fracture of a ceramic substrate is often unpredictable and can occur at any time during the processing or use of the circuit.

Recent disclosures have suggested that increasing the strength of a thin ceramic substrate would increase the resistance to the above-mentioned thermal shock and, in addition, increase the resistance to fracture during masking and handling. P. L. Gutshall and G. E. Gross in a technical publication entitled "Fracture Equals Strength" published in Ceramic Age, Vol. 84, No. 9 (1968), pp. 22-24, dealt with the problem of obtaining suitable strength thin ceramic bodies. Disclosed in the publication is a theory that polycrystalline ceramic bodies could achieve maximum strength properties if their structural makeup consisted of a fine grain exterior region and a coarse grain interior region.

A recent copending, coassigned application, Ser. No. 634,370, dated Apr. 22, 1967, to Stetson et al., entitled "Improvement in Alumina Substrates" discloses a method for manufacturing extremely thin ceramic substrates which have higher strength properties than commercially available ceramic substrates of equivalent thickness. A study of the structure of substrates produced by the Stetson et al. process reveals that the Gutshall et al. theory was met inherently in these substrates. More precisely, as a result of a grain growth inhibitor employed in the Stetson et al. process, the interior region of the substrate is approximately 1/4 times greater than the exterior region grain size of the substrate.

SUMMARY OF THE INVENTION

This invention provides a method wherein the strength of a thin ceramic substrate, of the general type produced by the above referred to Stetson et al. method, is further increased to the extent that fracture in the substrate is virtually eliminated. Moreover, the increased strength properties allow for a decrease in the thickness of the substrate, which consequently results in the reduction in amount of starting materials employed, and the reduction in the weight of the finished product.

To this end, the method of the present invention employs a technique based on the Stetson et al. process, whereby the size differential between the exterior region and interior region of a ceramic body, complementary types of "grain size control agents" are employed.

For purposes of this disclosure, a "grain size control agent" is an additive to a ceramic composition which either (1) inhibits or "retards" the grain growth of the ceramic, or (2) promotes or "accelerates" the grain growth of the ceramic. Other than controlling the grain growth of the ceramic, the grain growth agent, be it inhibitor or promoter, is otherwise inert to the ceramic composition. Well known grain growth inhibitors for a ceramic composition (such as aluminum oxide) are talc and the oxides of magnesium, nickel, and yttrium. Likewise, well known grain growth promoters for such a ceramic composition are the oxides of manganese and titanium.

To produce bodies having the improved structure as described, the method of the invention involves forming a multilayer ceramic body (illustratively of aluminum oxide) having grain growth inhibitors added to some of the layers and having grain growth promoters added to other layers.

Illustratively, a first batch of a high aluminum oxide composition which includes a small amount of talc as a grain growth inhibitor is prepared substantially as outlined in the Stetson et al. application. A second batch of a similar high aluminum oxide composition which includes a small amount of manganese oxide as a grain growth promoter is also prepared. From the first batch, a thin first layer of the composition is cast upon a suitable supporting surface. From the second batch, a thicker second layer of the composition is cast over the first layer. Again, from the first batch, a third layer of the composition, identical in thickness to the first layer, is cast over the second layer. The multilayer composite is then dried and fired in a continuous furnace to the sintering temperature of the composition, which is approximately 1,500°C. The resultant product is a dense, multilayer structure having an internal region grain size approximately twice that of the exterior region grain size.

DESCRIPTION OF THE DRAWING

The aforementioned and other features of the invention will become apparent from the following detailed description of the specific embodiments thereof when read in conjunction with the accompanying drawing, in which:

FIG. 1 is a perspective view of a slip casting device used in preparing the present invention;
FIG. 2 is a cutaway side view of the device in FIG. 1 showing a slip reservoir and doctor blade arrangement in specific detail;
FIG. 3 is a perspective view of a cast ceramic article produced by the process of the present invention;
FIG. 4 is a view similar to that of FIG. 2, showing a modified doctor blade arrangement;
FIG. 5 is a series of photomicrographic views illustrating the grain structure of the exterior region of different sintered ceramic substrates produced by the process of the present invention; and
FIG. 6 is a series of similar photomicrographic views as that of FIG. 5 illustrating the grain structure of the interior region of the substrate.

DETAILED DESCRIPTION

In order to further understand the present invention, it must be clearly distinguished from the aforementioned Stetson et al. invention. Stetson et al. are concerned with obtaining a smooth surface finish on a sintered, cast aluminum oxide substrate. This is desirable because a micro-thin film electric circuit requires a smooth surface insulating support in order to possess the desired electrical properties. Stetson et al. accomplish this end by employing a novel composition having as a principle constituent aluminum oxide (hereinafter called alumina). Another essential constituent of the Stetson et al. composition is an inorganic grain growth inhibitor. The grain growth inhibitor, combined with other organic constituents which are equally important to the composition, has a profound effect in retarding the crystal growth of the alumina
constituent during the sintering thereof. As a result, the sintered alumina crystals are extremely small, less than one micron in diameter, and this small size enhances the smoothness of the surface. The present invention modifies the Stottrup et al. process to improve the strength properties of a substrate.

In an illustrative embodiment of the invention, an alumina composition is first made into two separate slurries (hereafter, slips). The first slip when cast constitutes the exterior layers, and the second slip when cast constitutes the interior layer of a triple-layer ceramic substrate made according to the present invention.

Alcoa A-16 is a preferred alumina constituent of the slips because of its purity and fineness. It has an alumina content of over 99.9 percent purity and has, in addition, a nominal surface area of 11 m²/gm. However, other high purity aluminas may also be used, since the surface area of the material in the nominal state is not critical.

The slip is subjected to a milling operation to increase the surface area to an optimum value and 15 m²/gm. The time spent in milling a batch of alumina to an optimum surface area depends on two major factors; (a) the nominal surface area, and (b) the milling equipment employed. In order to attain a homogeneous end product, it is important that the alumina in each of the two slips be treated identically in this regard.

The alumina of the first slip composition has added thereto the grain growth inhibitor in amounts up to 0.5 percent by weight of the alumina composition. The alumina of the second slip composition has added thereto the grain growth promoter in amounts ranging from 0.2 to 0.5 percent by weight of the alumina in the composition.

As previously mentioned, the grain growth agents must be inert to the alumina. In addition, it is desirable that they possess similar physical properties to that of the alumina, such as surface area. Talc (H₂Mg₃Si₂O₇) is a preferred inhibitor because it is readily available, cheap, and comes as a very fine powder. Likewise, manganese oxide (MnO) is a preferred promoter in these respects. In addition, MnO seems to promote grain growth more than other promoters when used in equivalent amounts. The amount of grain control agent added to the composition should be held to a minimum consistent with the desired effect. Other inhibitors which have proven to be satisfactory for use are magnesium oxide (MgO) and yttrium oxide (Y₂O₃). Other useful promoters are titanium oxide (TiO₂) and niobium oxide (Nb₂O₅).

The milling is carried out in the presence of a liquid solvent. Suitable solvents are trichloroethylene, ethyl alcohol, and mixtures thereof. The proportion of alumina to solvent added for milling is not critical so long as the mixture has a watery or milklike consistency.

It is also essential that a deflocculant be used during the milling to keep the alumina evenly dispersed in the solvent, that is, to prevent the alumina from agglomerating. Fatty acids and synthetic surfactants such as the benzene sulfonic acids are suitable deflocculants. Natural fish oils perform very well, and in particular, menhaden oil is preferred as the deflocculant. In an alternative embodiment, the alumina composition is cast as a very thin layer of slip composition to be cast. For a three-layer cast slip composition having an outer layer as-cast thickness of 0.010 in. and a middle layer of slip composition to be cast.

The material is milled to a surface area of at least 12 m²/gm. The Alcoa A-16 alumina is the preferred starting material, and it is heated for 15 m²/gm. For the Alcoa A-16 alumina to be as-cast, it generally takes about 120 hours to obtain a 15 m²/gm. Surface area employing a laboratory type mill.

The binder is milled and one or more plasticizers are added to each slip composition, and the compositions are further blended in the mills for a time sufficient for complete mixing to take place. This period is usually approximately 8 hours. The function of the binder is to retain the alumina particles in undisrupted position after the organic solvent is evaporated, that is, to hold the cast article without itself sticking to the surface until it is fired into a hard ceramic. With the present invention, the preferred casting surfaces are formed from cellulose acetate, or from one of the fluorohalocarbon films made from fluorinated-chlorinated resins and marketed under the names "Mylar" and "Aclar" by Allied Chemical Co. A chromium plated stainless steel belt can also be used as a casting surface. For casting on these surfaces, polyvinyl butyral resins are preferred as binders. Several grades of polyvinyl butyral resins are marketed under the name "Butvar" by the Shawinigan Resin Corp. A Butvar B-98 grade resin is preferred. Other satisfactory binders are polyvinyl methylacrylate resin and cellulose acetate butyrate resin.

The function of the plasticizer is to improve the flexibility and workability of the cast ceramic article after drying. As plasticizers for polyvinyl butyral resin binders, excellent results have been obtained by mixing about 1 part of glycol with about 1 part of a mixed pthalate ester of normal hexyl, octyl, or decyl alcohols such as is marketed by Allied Chemical Co. under the name Elastex P-61. The glycol plasticizer which is preferred is marketed by Union Carbide Corp. as UCON 2000.

The binder is added in an amount approximately 5 percent by weight of the alumina, and the mixture of plasticizers is added generally in an amount approximately 13 percent by weight of the alumina.

The milled slip compositions are poured into closed containers for vacuum degassing for a short period of time (i.e., 3 minutes) and are then ready for casting. The finished slip compositions have the appearance and viscosity of heavy cream and are completely smooth.

Referring now to the drawing, with particular reference to FIGS. 1 and 2, there is shown apparatus which is preferred for casting the above two slip compositions. A casting surface 1 supports a continuous, elongated, movable plastic carrier tape 2 (e.g., of cellulose acetate). Fixedly positioned directly above and in alignment with the tape 12 is a reservoir 13 having open compartments 14, 16, and 17, respectively positioned in side-by-side relationship for casting the slip compositions as described below. The compartments 14, 16, and 17 are defined by fixed sidewalls 18 and 19, a fixed outer wall 21, and vertically adjustable gates 22, 23, and 24, which are spaced apart within the reservoir 13 and in parallel alignment with the end wall 21. As best seen in FIG. 2, the adjustable gates 22, 23, and 24 have bevelled shaped bottoms 22a, 23a, and 24a, which conveniently serve as doctor blades during the casting of the slip compositions in compartments 14, 16, and 17. The distance between the doctor blade 22a of gate 22 and the casting tape 12 is less than the distance between the doctor blade 23a of gate 23 and the casting tape. Correspondingly, the distance between the doctor blade 23a of gate 23 and the casting tape 12 is less than the distance between the doctor blade 24a of gate 24 and the casting tape. The distances are adjustable by vertically raising gates 22, 23, and 24 to a height corresponding to the desired thickness of each layer of slip composition to be cast.

In a specific illustration of the casting process, the gates 22, 23, and 24 are first adjusted to provide for a desired thickness for each layer of slip composition to be cast. For a three-layer cast slip composition having an outer layer as-cast thickness of
5 mills on both sides and an inner layer as-cast thickness of 20 mils, gate 22 would be adjusted so that its corresponding doctor blade 22a is 5 mills from the casting tape 12; gate 23 would be adjusted so that its doctor blade 23a is 25 mills from the casting tape; and gate 24 would be adjusted so that its doctor blade 24a is 30 mills from the casting tape. The casting tape 12 is next set in motion by actuating a drum pulling mechanism (not shown) which winds the tape in the direction of an arrow 26. The slip compositions are next successively pumped into the compartments 14, 16, and 17, respectively, at a rate of speed at least equal to the rate of speed of the now moving casting tape 12. Compartments 14 and 17 each receive quantities only of the first slip composition which has the inhibitor additive while compartment 16 receives a quantity of only the second slip composition which has the promoter additive.

Since the compartments 14, 16, and 17 are open, the first slip composition is deposited on the continuous moving tape 12 as slip is being pumped into compartment 14. While moving from under the compartment 14, the deposited slip composition is troweled by the doctor blade 22a of gate 22 to produce a first layer 27. This layer immediately passes under open compartment 16. A second slip composition is then continuously deposited on the moving first layer 27 as slip is being pumped into the compartment 16. During the movement from under compartment 16, the second slip composition is troweled by the doctor blade 23a of gate 23 to produce a second, superposed layer 28. The superposed first and second layers pass immediately under the third compartment 17, and the first slip composition pumped therein is deposited on the overlying layer 28. During the movement from under the compartment 17, the last deposited slip composition is troweled by the doctor blade 24a of gate 24 to produce a third superposed layer 29. The cellulose acetate carrier tape 12 provides for a smooth bottom surface to the first layer 27.

A three layer composite structure 31 of indefinite length emerges from under the reservoir 13 and continuously moves along the casting surface 11 on the casting tape 12. During this conveyance, the solvent in the layer composition evaporates rapidly to harden the structure 31. The solvent will completely vaporize at ordinary room temperatures. After a few hours of forced air drying, the structure 31 assumes the form of a leathery, hard tape, which can be punched into substrates of desired size. As best seen in FIG. 3, each such substrate (designated 31A) consists of the two cast outer layers 27 and 29 having the grain growth inhibitor and the inner layer 28 having the grain growth promoter. The substrate is next fired to a temperature within the range 1,450°-1,500° C. for approximately 3 hours.

Substrates produced in the above manner typically have (1) a surface smoothness comparable to the surface smoothness of substrate formed with the Stetson et al. process; (2) an interior grain size at least twice the size of the exterior grain size; and (3) strength properties that are 30-40 percent greater than the strength of the substrates produced by Stetson et al. process.

As stated previously, the amount of solvent included in the slip composition need not be critical. However, if the slip is too viscous, disproportionate flattening of the bottom layer 27 of the cast structure 31 might occur by the downward forces exerted by the corresponding upper layers 28 and 29. On the other hand, if the slip composition is too watery, the cast layers 27, 28, and 29 might intermix during the casting of the structure 31.

Referring now to FIG. 4, a modified doctor blade arrangement is shown which minimizes the aforementioned flattening or intermixing of the cast layers.

With like reference to identical parts shown in FIGS. 1 and 2, a first elongated flat member 32 is positioned within the compartment 16 at an angle to the adjustable gate 23 to produce a trough 33 within the compartment 16. Similarly, a second elongated member 34 is positioned in like manner in compartment 17 so that the gate 24 and the member 34 produce a second trough 36 within the compartment 17. The member 32 in compartment 16 is spaced from the casting tape 12 a sufficient distance to permit a cast layer 27 emerging from the preceding compartment 14 to pass thereunder. Likewise, the member 34 in compartment 17 is sufficiently spaced from the casting tape 12 to allow a casting having layers 27 and 29 emerging from the preceding compartment 16 to pass thereunder.

In the operation of FIG. 4, gate 22 is adjusted in a manner similar to FIG. 2, to be spaced from the casting tape 12 by a distance sufficient to produce a desired thickness in cast bottom layer 27. Gates 23 and 24 are vertically adjusted so as to produce openings 32a and 34a between the doctor blades 23a and 24a respective bottom ends 32b and 34b of the members 32 and 34 to provide a desired thickness for the cast layers 28 and 29. The casting tape 12 is set in motion as outlined in FIG. 2 in a direction 26 and the appropriate slip composition is first pumped into the compartment 14. Next, the slip compositions used to cast layers 28 and 29 are successively pumped into the respective troughs 33 and 34. The troughs 33 and 34 produce a baffle arrangement for casting the slip that produces layers 28 and 29. Thus, the bottom cast layer 27 emerging from under the doctor blade 22a is conveyed completely under compartment 16 before the slip composition for the inner cast layer 28 is deposited thereon. Likewise, inner cast layer 29 emerging from under the doctor blade 23a is conveyed completely under compartment 17 before the slip composition for the upper cast layer 29 is deposited thereon. As a result, each of the layers 27 and 28 are exposed to the atmosphere of the unfilled portion of reservoirs 16 and 17, respectively, for a short period of time. This allows each layer to partially set before the subsequent layer is deposited thereon. Thus, if the slip compositions are slightly too viscous, the additional time allowed for the partial set of the bottom layer 27 will give added strength thereto to protect against undue flattening when the upper layers 28 and 29 are deposited thereon. Moreover, if the slip compositions are slightly too watery, the added time for partial set will render the bottom cast layer 27 sufficiently rigid to prevent intermixing when the upper layers are cast thereon.

Without limiting the generality of the foregoing description, the following examples are presented to illustrate the strength properties obtainable by the method embodying the present invention:

**EXAMPLE 1**

The following batches of the below listed proportionately mixed constituents were placed in separate laboratory type high alumina mills.

**BATCH NO. 1**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcoa A-16 Alumina</td>
<td>99.8</td>
</tr>
<tr>
<td>Yttrium Oxide (Y₂O₃)</td>
<td>0.1</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**BATCH NO. 2**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcoa A-16 Alumina</td>
<td>99.5</td>
</tr>
<tr>
<td>Manganese Oxide (MnO)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

To each mixture there was added a TCE-Alcohol solvent, which is a mixture of 72 percent trichloroethylene and 28 percent ethyl alcohol. The solvent was added in amounts of 70 grams per 100 grams of each oxide mixture.

Another addition to each mixture was a menhaden oil deflocculant, known commercially as Ensign Z-3. The deflocculant was added in amounts of 1.8 grams per 100 grams of each mixture.

Half of the volume of the mill contained charges of high alumina spheres as the grinding media. Milling was carried out for 120 hours.
3,652,378

At the completion of the milling, to each batch mixture there was added a butyral resin, specifically a Butvar B-98 binder. The binder was added in amounts of 5.5 grams per 100 grams of oxide mixture. Also added to the milled mixture was a mixture of Elastex P-61, which is a polyalkylene glycol plasticizer, and Ucon 2000, which is a phthalate ester plasticizer. The plasticizers were added in amounts of 11 grams per 100 grams of oxide mixture, 5 grams of which was the glycol plasticizer and 6 grams of which was the phthalate plasticizer.

Each mixture was milled for an additional 8 hours to assure thorough dispersion of all ingredients in the slip. The finished slip compositions were transferred from the mills to separate closed containers and de-aired in a vacuum of approximately 4 inches of Hg, for a period of 3 minutes.

The slip compositions were cast into layers on a cellulose acetate film supported on glass using the doctor blade arrangement shown in FIG. 2. The slip compositions produced from batch No. 1 made up the exterior layers, and the slip compositions produced from batch No. 2 made up the interior layer. The apparatus was adjusted to produce a layered article having a final fired thickness of 0.025 in., with the exterior layers having a thickness of 0.005 in. and the interior layer having a thickness of 0.015 in. After casting the composite cast tape was forced-air dried. The cast tape was stripped from the cellulose acetate tape and substrates were then punched from the cast tape.

The substrates were laid on flat, fired ceramic supports in preparation for firing. Each substrate was covered with a previously fired substrate of the same general dimensions to prevent warping during the firing. The firings were performed in an Ipsen Roller Hearth Kiln at temperatures ranging from 1,450°-1,515°C., the firing cycle ranging from 1 to 3 hours. Some of the substrates were fired in one cycle and others were fired in a two-pass schedule.

The resulting substrates were flat, had a surface or exterior region average grain size of 0.78 microns, an internal average grain size of 1.48 microns. The substrates had an average flexural strength of approximately 119,000 p.s.i.

For comparison, a second group of homogeneous substrates containing only the mixture in batch No. 1 was cast to yield a fired thickness of 0.025 in. These substrates were dried and fired in accordance with the above procedures and their flexural strengths were measured. The average flexural strength of these substrates was less than 100,000 p.s.i.

A third group of homogeneous substrates containing only the mixture in batch No. 2 was cast to yield a fired thickness of 0.025 in. Drying and firing were completed in accordance with the above procedures, and again, the flexural strength of each substrate was measured. The average flexural strength of these substrates was only approximately 72,000 p.s.i.

**EXAMPLE 2**

A measured amount of the listed proportionately mixed constituents were placed in separate size 2 laboratory-type, borundum fortified mills.

**BATCH NO. 3**

<table>
<thead>
<tr>
<th>Alumina A-16</th>
<th>99.5 wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yule</td>
<td>0.5 wt%</td>
</tr>
</tbody>
</table>

**BATCH NO. 4**

<table>
<thead>
<tr>
<th>Alumina A-16 Alumina</th>
<th>99.5 wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese Oxide (MnO)</td>
<td>0.5 wt%</td>
</tr>
</tbody>
</table>

A charge of cylindrical borundum was employed as the grinding media for each mill. Each slip composition was prepared as outlined in Example 1.

The resulting slip compositions were cast into layers on a similar cellulose acetate support as in Example 1, this time using the doctor blade arrangement as outlined in FIG. 4. The casting, drying, and firing were also carried out essentially as outlined in Example 1. The resulting substrates had an average external region grain size of 0.82 microns, and an average internal region grain size of 1.93 microns, and an average flexural strength of approximately 118,000 p.s.i.

Referring now to FIGS. 5 and 6, there are shown views of substrates of this type which were photographed under an electron microscope and magnified 10,000 times. FIG. 5 represents the exterior or surface region structure of two typical substrates while FIG. 6 represents the internal region structure of the respective substrates. The substrate of FIG. 5a and FIG. 6a was fired in one cycle, and the substrate of FIG. 5b and FIG. 6b was fired in two cycles (fired twice). It can be observed from the photomicrographs in FIG. 5 that the grain size of the external region of each substrate is much smaller than the grain size of the internal region of the corresponding substrate as illustrated in FIG. 6.

For comparison, a second group of homogeneous substrates containing only the mixture in batch No. 3 was manufactured essentially as outlined above and processed as in FIG. 4. The substrates had an average external grain size of 0.73 microns, and an average internal grain size of 0.97 microns, and an average flexural strength of only 87,000 p.s.i.

What is claimed is:

1. A method for manufacturing a ceramic body that has a relatively small external grain size structure and a relatively large interior grain size structure, which comprises the steps of:

   - casting a first layer of a first alumina slip composition which has as one of its constituents an added grain growth inhibitor;
   - casting on the first layer a second superposed layer of a second alumina slip composition which has as one of its constituents an added grain growth promoter in amounts ranging from 0.2 to 0.5 percent by weight of the slip composition;
   - casting on the second layer a third superposed layer of the first slip composition;
   - heating the superposed layers to (a) sinter the layers into a composite structure, (b) cause the inhibitor in the first and third layers to retard the grain growth in the respective layers, and (c) cause the promoter in the second layer to accelerate the grain growth in the layer, thereby producing a ceramic body having a relatively small exterior grain size and a relatively large interior grain size.

2. The method of claim 1 wherein the principle constituent of the slip composition is alumina.

3. The method of claim 2 wherein the grain growth inhibitor is selected from the group consisting essentially of talc and the oxides of magnesium and yttrium.

4. The method of claim 3 wherein the grain growth inhibitor is talc.

5. The method of claim 3 wherein the grain growth inhibitor is a mixture of magnesium and yttrium oxides.

6. The method of claim 2 wherein the grain growth promoter is selected from the group consisting essentially of the oxides of manganese, niobium, and titanium.

7. The method of claim 6 wherein the grain growth promoter is manganese oxide.

8. A method of manufacturing a three-layer alumina substrate having high strength properties and characterized by a fine grain surface and a coarse grain interior which comprises the steps of:

   - preparing a first alumina slip composition having a small amount of an added inorganic grain growth inhibitor;
   - preparing a second alumina slip composition having an added inorganic grain growth promoter in amounts ranging from 0.2 to 0.5 percent by weight of the alumina;
   - separately pulverizing the particles of each slip composition prior to the preparation of slip until the particles attain a surface area in the range of 12-15 m²/gm.
de-airing each slip; depositing a quantity of the first slip onto a moving supporting surface; forming the deposited first slip into an indefinite length first layer having a first thickness; depositing a quantity of the second slip over the first layer; forming the deposited second slip into an indefinite length second layer superposed on the first layer and having a second thickness; depositing an additional quantity of the first slip over the second layer; forming the additional deposited first slip into an indefinite length third layer superposed over the second layer and having a third thickness; drying the three superposed layers to produce a composite triple-layer structure; severing a plurality of definite length pieces from the indefinite length composite structure to form individual triple-layer structures; and firing the substrates to (a) sinter the substrates, (b) cause the inhibitor in the first and third layers of each substrate to retard the grain growth in the respective layers, and (c) cause the promoter in the second layer to accelerate the grain growth in the second layer, thereby causing each substrate to have a fine grain surface and a coarse grain interior.

9. The method of claim 8 wherein the inhibitor is talc added in amounts of 0.5 wt% of the alumina.

10. The method of claim 8 wherein the inhibitor is a mixture of magnesium and yttrium oxides, each constituent of the mixture being added in amounts of 0.1 wt% of the alumina.

11. The method of claim 8 wherein the promoter is manganese oxide added in amounts of 0.5 wt% of the alumina.

12. The method of claim 8 wherein the compositions are prepared in the form of a slip and are deposited by slip casting.

13. The method of claim 8 wherein the forming is accomplished by troweling.

14. The method of claim 8 wherein the sintering is effected by firing in the range of 1,450º - 1,515º C. for 3 - 6 hours.

15. A slip cast, high-strength, triple-layer alumina body having an added inorganic grain growth inhibitor in each of its exterior layers and an added inorganic grain growth promoter in its interior layer, the amount of promoter ranging from 0.2 to 0.5 percent by weight of alumina in the layer.

* * * *