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PROCESS FOR THE PRODUCTION OF METAL NITRIDE SINTERED BODIES
AND RESULTANT SILICON NITRIDE AND ALUMINUM NITRIDE SINTERED BODIES

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Title: Process for the Production of Metal Nitride Sintered Bodies and Resultant Silicon Nitride and Aluminum Nitride Sintered Bodies

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Patent Claims

1. Process for the production of metal nitride sintered products, characterized by the fact that metal nitride powder is mixed, shaped to the desired form and heated under reduced pressure, inert gas, CO gas and/or hydrogen gas with at least one binding agent from the following group:

   (1) compounds in which the silicon is bound only to carbon;
   (2) compounds with Si-H bonds in addition to Si-C bonds;
   (3) compounds with Si-Hal bonds;
   (4) compounds with Si-Si bonds;
   (5) compounds with Si-N bonds and
   (6) high molecular weight organosilicon compounds in which silicon and carbon are main structural components and which are formed by polycondensation of at least one of the organosilicon compounds from groups (1) through (5) above and from
   (7) organoalkoxy- (or -aryloxy-)silanes;
   (8) compounds with Si-OH bonds;
   (9) compounds with Si-O-Si bonds;
   (10) esters of organosilicon compounds and
   (11) peroxides of organosilicon compounds

to form metal nitride sintered products.

2. Process according to Claim 1, characterized by the fact that the metal nitride sintered product is heated to a temperature of 800 to 1400°C in an oxidizing atmosphere to remove free carbon contained in the metal nitride sintered product.

3. Process according to Claim 1, characterized by the fact that the binding agent is added in an amount of from 0.3 to 45% by weight.

4. Process according to Claim 1, characterized by the fact that the shaped briquette is heated to a temperature of 800 to 2200°C.

5. Process according to Claim 1, characterized by the fact that the mixture of metal nitride powder and binding agent is pressed by means of a hot-press procedure, during which sintering takes place.
6. Process according to Claim 1, characterized by the fact that the metal nitride sintered product is impregnated with a liquid form of the organosilicon compound or high molecular weight organosilicon compound under reduced pressure, and the impregnated metal nitride sintered product is then heated under vacuum, inert gas, CO gas and/or hydrogen gas.

7. Process according to Claim 6, characterized by the fact that the subsequent treatment of impregnation and heating is carried out or repeated two or more times.

8. Process according to Claim 6, characterized by the fact that the impregnated metal nitride sintered product is heated to a temperature of 800 to 2200°C.

9. Process according to Claim 6, characterized by the fact that the liquid form of the organosilicon compound or high molecular weight organosilicon compound is produced by dissolving same in a solvent.

10. Process according to Claim 1, characterized by the fact that Si$_3$N$_4$ or AlN is used as the metal nitride.

11. Si$_3$N$_4$ sintered products characterized by a content of SiC binding agent, flexural strength of no less than 5 kg/mm$^2$, effective density of no more than 3.05 g/cm$^3$ and high dimensional accuracy.

12. AlN sintered products characterized by a content of SiC binding agent, flexural strength of no less than 3 kg/mm$^3$, effective density of no more than 3.0 g/cm$^3$ and high dimensional accuracy.

* (Translator's note: appears to be misprint in German original; should be kg/mm$^2$)
The invention concerns a process for the manufacture of metal nitride sintered bodies and, in particular, a process in which a mixture of metal nitride powders is shaped and heated together with a binding agent.

Of the metal nitrides, Si₃N₄ and AlN were used especially frequently because of their excellent properties at high temperatures; sintered bodies of these metal nitrides were made according to the following processes:

(1) Production of Si₃N₄ Sintered Bodies

In general, silicon powders are shaped and the briquettes are heated in nitrogen or ammonia gas, resulting in simultaneous nitride formation and sintering. However, the self-sintering capacity of Si₃N₄...
is low and the sintered bodies made from Si\textsubscript{3}N\textsubscript{4} according to the conventional processes have a porosity of about 20\% and a low density of roughly 1.2 to 2.7 g/cm\textsuperscript{3}, which is far below the theoretical value of 3.18 g/cm\textsuperscript{3}, and they become markedly oxidized at temperatures of about 1200°C. According to a relatively new process, MgO, Al\textsubscript{2}O\textsubscript{3}, Y\textsubscript{2}O\textsubscript{3}, and similar compounds are added to Si\textsubscript{3}N\textsubscript{4} powder and the mixture is ground, shaped and sintered, resulting in dense Si\textsubscript{3}N\textsubscript{4} sintered bodies with high oxidation resistance.

One Si\textsubscript{3}N\textsubscript{4} sintered product known as "Sialon", with a high density close to the theoretical value, was recently produced by adding several percent Al\textsubscript{2}O\textsubscript{3} or Y\textsubscript{2}O\textsubscript{3} as binding agent to Si\textsubscript{3}N\textsubscript{4} powders in a hot-press process. However, inclusion of various impurities such as MgO, Al\textsubscript{2}O\textsubscript{3}, Y\textsubscript{2}O\textsubscript{3} and similar compounds in the sintered products cannot be avoided in the processes described above.

(2) Production of AlN Sintered Bodies

Generally, aluminum nitride powders are subjected to a hot-press process, or aluminum nitride alone is shaped and sintered, or aluminum nitride is added to aluminum powder and the mixture is subjected to a nitriding and sintering treatment. Irrespective of the hot-press process, these procedures do not produce sintered bodies of sufficient density, and high treatment temperatures of about 1700 to 2000 °C are required and the strength of the resulting AlN sintered products is low. Indeed, sintered products with relatively high density of roughly 98\% of the theoretical value can be obtained using the hot-press process, but their strengths are at most about 30 kg/mm\textsuperscript{2}, which is far from a satisfactory strength value. Recently, it was reported that an AlN fibrous structure was formed by sintering a mixture of AlN with small amounts of Y\textsubscript{2}O\textsubscript{3}, resulting in AlN sintered products of high mechanical strength.

In the procedures described above, however, inclusion of Y\textsubscript{2}O\textsubscript{3} as an impurity in the sintered product cannot be avoided, just as in the production of Si\textsubscript{3}N\textsubscript{4} sintered bodies.

In other words, if Si\textsubscript{3}N\textsubscript{4} or AlN sintered products are produced according to the above procedures (1) or (2) and are used as tubes, crucibles or boats in the production of high-purity metals, the oxides used as binding agents -- MgO, Al\textsubscript{2}O\textsubscript{3}, Y\textsubscript{2}O\textsubscript{3} in the case of Si\textsubscript{3}N\textsubscript{4}
sintered products and \( \text{Y}_2\text{O}_3 \) in the case of \( \text{AlN} \) sintered products -- react with the metal or metals at high temperatures and the resulting sintered products have a low thermal shock strength, thereby limiting the usefulness of such sintered products with oxide inclusions.

The goal of the invention, therefore, is a process for the production of metal nitride sintered bodies with high strength and other excellent properties such as high corrosion resistance and thermal shock resistance, and in which the previously known faults of the metal nitride sintered products are avoided.

According to the invention, metal nitride powders are mixed with at least one of the binding agents from the following group of organosilicon compounds:

1. compounds in which Si is bound only to C ("which have only Si-C bonds");
2. compounds with Si-H bonds in addition to Si-C bonds;
3. compounds with Si-Hal bonds;
4. compounds with Si-Si bonds;
5. compounds with Si-N bonds; and
6. high molecular weight organosilicon compounds in which silicon and carbon are main structural components and which are obtained from polycondensation reactions of at least one of the organosilicon compounds (1) to (5) above; as well as from
7. organoalkoxy- (or aryloxy-) silanes (with Si-OR);
8. compounds with Si-OH bonds;
9. compounds with Si-O-Si bonds;
10. esters of organosilicon compounds; and
11. peroxides of organosilicon compounds.

The mixture is shaped to the desired form and the briquette is heated in vacuum, inert gas, CO gas and/or hydrogen gas, whereby the above organosilicon compounds and high molecular weight organosilicon compounds are thermally decomposed and the volatile components are evaporated, while the remaining carbon and silicon react to form SiC, and the above mixture can be sintered at a lower sintering temperature than in conventional processes.

Metal nitrides which can be used within the framework of the invention...
include Si₃N₄, AlN, HfN, TaN, ZrN, TiN, ScN, UN, ThN, NbN, VN, CrN, BN, Be₃N₂, etc. The use of fine-grained metal nitrides permits lower sintering temperatures and more dense sintered products.

The binding agents to be used according to the invention include the organosilicon compounds (1) to (5) mentioned earlier and the polycondensed, high-molecular organosilicon compounds having a molecular weight of 100 - 600,000. If the above organosilicon compounds (1) to (5) or the high molecular weight organosilicon compounds are mixed with the metal nitrides and the resulting mixture is shaped and heated, the named compounds are thermally decomposed and hydrogen, chlorine or a portion of the carbon volatilizes, while the remaining carbon and silicon react at a temperature higher than about 1250°C to form SiC, resulting in a sintered product which contains essentially SiC as well as Si₃N₄ or AlN as the main component. With regard to the above-named compounds (1) to (5), various oxygen-containing organosilicon compounds can be used in the formation of the sintered product, but in such cases small amounts of silicon dioxide are formed, which can detract from the properties of the sintered product and thereby limit the usefulness of same.

In the following, examples are presented for the above-mentioned organosilicon compounds (1) to (5) used as binding agents.

(1) Compounds in which the silicon is bound only to carbon:

This group includes silicon hydrocarbons such as R₄Si, R₂Si(R'SiR₂)ₙ - R'SiR₃ and carbo-functional derivatives of same, such as, for example:
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(2) Compounds with Si-H bonds in addition to Si-C bonds:

This group includes mono-, di- and triorganosilanes such as, for example:

\[
\begin{align*}
(C_2H_5)_2SiH_2, & \quad (CH_3)SiH_3, & \quad (CH_3)_2SiH, \\
C(CH_2SiH_3, & \quad HSi-C\equivC-SiH. \end{align*}
\]

(3) Compounds with Si-Hal bonds:

This group includes organohalosilanes such as, for example:

\[
\begin{align*}
CH_3SiCH_2F, & \quad C_2H_5SiHCl, \\
(CH_3)_2(C\equivCH)SiSi(CH_3)_2Cl, & \quad (C_2H_5)_2SiBr. \end{align*}
\]
(4) Compounds with Si-Si bonds:

Examples include:

\[
\begin{align*}
(CH_3)_2SiSi(CH_3)Cl, & \quad (C_6H_5)_2SiSi(C_6H_5)Si(CH_3) \ldots \\
\end{align*}
\]

(5) Compounds with Si-N bonds:

This group includes silylamines such as, for example:

In the above structures, R indicates an alkyl or aryl group.
According to the invention, the binding agent can be an organosilicon compound from groups (1) to (5) above or from the high molecular weight organosilicon compounds formed from polycondensation of the former, or compounds formed from the following organosilicon compounds (groups 7 through 11) by means of radiation, thermal reaction or addition of polycondensation catalysts according to known processes.

(7) Organoalkoxy- (or -aryloxy-) silanes (with Si-OR): Examples include:

![Chemical structure](image1)

(8) Compounds with Si-CH bonds:

This group includes organosilanes or organosilanols such as, for example:

![Chemical structure](image2)
(9) Compounds with Si-O-Si bonds:

This group includes organosiloxanes such as, for example:

![Chemical structures of Si-O-Si compounds]

(10) Esters of organosilicon compounds:

This group includes esters of silanols and acids, for example:

\[(\text{CH}_3)_2\text{Si(OOCR)}_2\]
(11) Peroxides of organosilicon compounds such as, for example:

\[(\text{CH}_3)_3\text{SiOC} \cdot (\text{CH}_3)_3, (\text{CH}_3)_3\text{SiO} \cdot \text{Si}(\text{CH}_3)_3\]

In the above formulas, \( R \) once again indicates an alkyl or aryl group.

From these starting materials, high molecular weight organosilicon compounds are obtained, in which silicon and carbon are the main structural components. For example, compounds with the following molecular structures are produced:

(d) Compounds with the above structural components (a) through (c) forming at least a partial structure in linear, cyclic and three-dimensional structures or mixtures of compounds with the above structural components (a) through (c).

Compounds having the molecular structures described above include, for example, the following:

(a) \( -\text{Si-}(\text{C})_n\text{-Si-O-} \)

\( n=1 \), poly(silmethylene siloxane),
\( n=2 \), poly(silethylene siloxane),
\( n=6 \), poly(silphenylene siloxane)
(b) $\text{-Si-O-(C)}_n\text{-O-}$

$n=1$, poly(methylene oxysiloxane),
$n=2$, poly(ethylene oxysiloxane),
$n=6$, poly(phenylene oxysiloxane),
$n=12$, poly(diphenylene oxysiloxane)

(c) $\text{-Si-(C)}_n\text{-}$

$n=1$, polysilmethylene,
$n=2$, polysilethylene,
$n=3$, polsiltrimethylene,
$n=6$, polysilphenylene,
$n=12$, polysildiphenylene.

(d) Compounds with the above structural components forming at least a partial structure in linear, cyclic and three-dimensional structures or mixtures of compounds with the above structural components (a) through (c).

With the high molecular weight organosilicon compounds with silicon and carbon as main structural components, the silicon or carbon, even if these are present in side chains, easily decompose or split off and volatilize, while silicon and carbon which form main structural components do not easily decompose or volatilize with heat, but react at high temperatures to form SiC.

The production of high molecular weight organosilicon compounds in which silicon and carbon are the main structural components, starting from initial organosilicon compounds belonging to the above named groups (1) to (5) and (7) to (11), can take place by polycondensation reaction in which the organosilicon compound is subjected to radiation, heat, or addition of a polycondensation catalyst.

Examples of several known reactions for the production of the named high molecular weight organosilicon compounds from the initial materials of groups (1) to (5) and (7) to (11) by catalyst addition, radiation and/or heating are given in the following:
Apart from the above named processes for the production of high molecular weight organosilicon compounds, at least one organosilicon compound from groups (1) to (5) and (7) to (11) is polymerized within a temperature range of 200 to 1500°C under vacuum, inert gas, CO gas or hydrogen gas under pressure, if necessary, to form the high molecular weight organosilicon compounds in which silicon and carbon are the main structural components.

The reason for carrying out the above reaction within a temperature range of 200 to 1500°C is the following: If the temperature is below 200°C, the synthesis reaction does not proceed satisfactorily, while at temperatures above 1500°C the decomposition reaction is intense and the yield of high molecular weight organosilicon compound is low; therefore, the temperature must be in the range 200 to 1500°C and the best results can be achieved within the range 300 to 1200°C.

The above synthesis reaction can be carried out in a pressure vessel and in this case the optimal temperature range is 350 to 500°C; since the thermal decomposition reaction during polycondensation of the organosilicon compounds builds up pressure, it is not always necessary to apply (external) pressure. The polycondensation reaction described above can be performed in a continuously operating device. The following describes one such process employing a continuously operating device as shown in Fig. 4: The organosilicon compound is fed into a heated reaction column 2 through a valve 1 and is heated in the column to a temperature of 300 to 1500°C, preferably 500 to 1200°C. A portion of the reaction product consisting of high molecular weight organosilicon compound is removed from the system through a valve 3,
while low molecular weight compounds formed in the reaction column are fed into a fractionating column through a valve, distilled and separated. The gas formed in the fractionating column is removed through a valve and the high molecular weight compound through a valve. The low molecular weight compounds separated in the fractionating column are recycled to the reaction column through a valve.

The molecular structure of the resulting high molecular weight organosilicon compounds was examined by means of nuclear magnetic resonance spectroscopy and infrared spectroscopy, confirming the presence of Si-C bonds and the fact that the main structural components of the compounds were based on silicon and carbon.

The following describes a process which employs polycarbosilane as a binding agent. Among the binding agents named earlier, polycarbosilane is easily produced and exhibits the lowest weight loss following heat treatment.

Polycarbosilane is liquid or solid and can be used directly or in viscous solution of the solid in a solvent such as benzene, toluene, xylene, hexane, ether, tetrahydrofuran, dioxane, chloroform, methylene chloride, petroleum ether, gasoline, ligroin, DMSO, DMF and other solvents which dissolve polycarbosilane, as a binding agent in the production of metal nitride sintered products. Binding agents other than polycarbosilane can be used according to the above data by employing the polycarbosilane process.

The binding agent is added in amounts corresponding to 0.3 to 45% by weight with respect to the metal nitride powder. The amount added can be an amount which is necessary for the sintering of metal nitrides, and can be determined by the shaping and sintering process as described in the following. The resulting mixture is shaped into the prescribed form. Alternatively, a hot-press process can be used, in which the mixture is heated in a mold and pressing takes place during the sintering process.

Sintering of the above briquettes is achieved by heating to a temperature of 800 to 2200°C in vacuum, inert gas, CO gas and/or hydrogen gas.

If the heat treatment is done in air, the binding agent oxidizes to form SiC₂; therefore, heat treatment is preferably carried out in at least one of the named atmospheres, i.e. vacuum, inert gas, CO gas or hydrogen gas.
If the combustion procedure according to the hot-press process above is carried out under a pressure of 70 to 20,000 kg/cm\(^2\) in vacuum, inert gas, CO gas and/or hydrogen gas, conversion of the binding agent into SiC can be increased and a metal nitride sintered product of higher strength can be obtained. Furthermore, if the combustion process takes place in vacuum, conversion of the binding agent to SiC is increased if the heating temperature is raised for a sufficient period of time, resulting in dense sintered products of considerably greater strength.

The hot-press process according to the invention is a process for sintering high temperature-resistant powders which are not shaped beforehand, but rather heated in a mold and pressed during the sintering process, resulting in more densely packed products.

In industrial hot-press procedures, the temperature is generally 1500 to 2200°C and the pressure 100 to 700 kg/cm\(^2\). Furnace heating is generally electric by means of resistance heating or a high frequency induction heating process.

In resistance heating, the voltage is continuously increased from 0 V to 30 V and an induction regulator of 15,000 A is generally used, as well as a graphite resistance tube as the heating element, with thickness 1.3 cm, outside diameter 20 cm and length 150 cm. In the high frequency induction method, frequencies of 1000 to 40,000 Hz can be used. In a small scale hot-press process for the production of briquettes of diameter 2.5 cm and length 2.5 cm, 15 kVA at 30,000 Hz is recommended, and for large briquettes of diameter 35 cm and length 25 cm, 300 kVA at 1000 Hz is required.

The simplest pressing method is the lever type, which is not, however, suitable for pressure adjustment. An impact or die press type with oil pressure or air pressure is generally used.

If the mold is electrically conductive at temperatures of 1500 to 2200°C, which is the pressing temperature, heating can take place directly by means of resistance heating or an induction process, and generally employs graphite. There are many types of graphite, but for hot pressing dense graphite of the highest possible strength and machinability is most suitable.
The following describes in detail the sintering procedure for metal nitrides in the production of metal nitride sintered products. The organosilicon compounds and high molecular weight organosilicon compounds used as binding agents are thermally decomposed during heat treatment and excess carbon and hydrogen volatilizes; the remaining carbon and silicon react to form essentially SiC, which bonds with the metal nitride powders. During the course of this treatment, the organosilicon compound or high molecular weight organosilicon compound, if the temperature is gradually increased over a sufficient period of time, fills the interstices between the metal nitride powder grains and as combustion proceeds, the volatile components gradually vaporize and the remaining components react to form SiC, and self-sintering of the metal nitrides, whose self-diffusion is slow, is accelerated. In this case, the organosilicon compounds and high molecular weight organosilicon compounds added as binding agent decompose at a relatively low temperature, as shown in Fig. 1. Hydrogen, chlorine, and a portion of the carbon volatilize, while the remaining carbon and silicon react and at a temperature above about 1250°C are completely converted to SiC. Even if the metal nitride sintering temperature is lower than that in conventional sintering processes, high strength sintered products can be obtained with high oxidation and corrosion resistance as well as high thermal shock resistance. This is a characteristic feature of the invention. If the binding agent according to the invention is converted to SiC, microrcrystalline SiC is formed with a grain size of 30 to 70 µ, which is much smaller than in previously known SiC sintered products. The specific surface area is considerably larger and the effective self-diffusion coefficient of SiC is very high. The sinterability of the metal nitride products according to the invention is increased, resulting in sintered products of high strength.

Another feature of the invention is the fact that the binding agent used ultimately is converted to SiC, which has high oxidation resistance, corrosion resistance and the additional favorable property of hardly ever reacting with metals. SiC is industrially more preferable as a binding agent than oxides such as MgO, Al₂O₃, Y₂O₃ and similar compounds which have previously been used as binding agents for the metal nitrides.

It is possible to obtain sintered products of high strength by subjecting the products obtained above at least once to the following
secondary treatment: the sintered products are impregnated with a liquid form of the above organosilicon compounds or high molecular weight organosilicon compounds under reduced pressure of 1 torr and then heated to a temperature of 800 to 2200°C in vacuum, inert gas, hydrogen gas and/or CO gas. The above organosilicon compounds or high molecular weight organosilicon compounds must be used in liquid form, i.e. organosilicon compounds or high molecular weight organosilicon compounds which exist or which can be obtained in liquid form can be used directly or, if necessary, can be dissolved in a small amount of benzene, toluene, xylene, hexane, ether, tetrahydrofuran, dioxane, chloroform, methylene chloride, petroleum ether, gasoline, ligroin, DMSC, DMF or other solvents which dissolve the compounds, in order to reduce the viscosity. If the organosilicon compounds or high molecular weight organosilicon compounds used do not have satisfactory flow properties, it is advisable to use these compounds in solution form, i.e., dissolved in the solvents named above. As mentioned earlier, the organosilicon compounds include low molecular weight compounds as well as high molecular weight compounds formed by polycondensation of same; however, the latter are preferred as impregnating agents. Furthermore, by carrying out or repeating the secondary treatment described above at least once, sintered products of very high strength can be produced, even if sintering takes place at a relatively lower temperature than that in conventional sintering.

If, for example, Si$_3$N$_4$ sintered bodies are subjected five times to the impregnation procedure described above, the resulting flexural strength attains values of 20 to 40 kg/mm$^2$, even at the low sintering temperature of 1100°C. The effective density is low, 2.5 to 2.9 g/cm$^3$, and the weight is low, but the flexural strength is high. This is one of the features of the invention. Using known procedures, it is generally impossible to obtain Si$_3$N$_4$ sintered products at a temperature below 1500°C. Sintered products having the properties indicated above can be obtained at temperatures below 1500°C only with the process according to the invention. In addition, the size and/or dimensions of the Si$_3$N$_4$ sintered products obtained according to the invention do not change appreciably before and after combustion, signifying high dimensional accuracy. Even if shaped pieces of complex form are sintered, the dimensional accuracy of the sintered product is essentially the same before and after combustion, which is a note-
worthy characteristic of the invention compared to conventional procedures for the production of $\text{Si}_3\text{N}_4$ sintered bodies.

The metal nitride sintered bodies described above may contain free carbon, which can be removed by burning the sintered product at a temperature of 800 to 1400°C in an oxidizing atmosphere. If this combustion takes place at temperatures below 800°C, carbon cannot be removed, while at temperatures above 1400°C the oxidation reaction of the metal nitride becomes excessive, so such high temperatures are not recommended. The time required for this combustion in oxidizing atmosphere varies depending on the combustion temperature, the size of the pieces and the structure of the furnace. If the combustion temperature is low, long times are required, while at high combustion temperatures the required times can be short; if, however, combustion takes place at a lower temperature for a relatively long period of time, low quantities of metal oxide are formed and good results can be obtained. For example, the combustion time for a crucible produced according to the invention in air at a temperature of 1000°C for removal of free carbon is 1 to 3 hours.

In the metal nitride sintered bodies formed as described above, the binding agent is ultimately converted into SiC, so that the products do not contain impurities such as MgO, $\text{Al}_2\text{O}_3$, $\text{Y}_2\text{O}_3$, etc., which are commonly found in the products of conventional processes. The metal nitride sintered products according to the invention, compared to those of conventional processes, have greater oxidation and corrosion resistance and thermal shock resistance, as well as high strength even at lower densities.

As previously mentioned, the amount of binding agent added, according to the invention, is 0.3 to 45% by weight. With less than 0.3 wt.-%, it is difficult to obtain metal nitride sintered products of high strength, while more than 45% results in low effective density, lower strength and decreased oxidation resistance when used at high temperatures; therefore, the amount of binding agent added must be between 0.3 and 45% by weight. When using the hot-press method, the amount added is preferably 1 to 10 wt.-%, and in the procedure in which the mixture of metal nitride powder and binding agent is pressed and the formed mixture combusted, amounts of 3 to 15 wt.-% are preferred.
Si₃N₄ sintered products obtained according to the invention have flexural strength values of not less than 5 kg/mm², effective densities of not more than 3.05 g/cm³, high dimensional accuracy and high purity.

AlN sintered products obtained according to the invention have flexural strengths of not less than 3 kg/mm², effective densities of not more than 3.0 g/cm³, high dimensional accuracy and high purity.

In the following, the invention is described in more detail, with reference to the attached drawings. The drawings show:

Fig. 1: a plot illustrating the relationship between the heating temperature in vacuum and polycarbosilane residual weight;

Figs. 2 and 3: plots illustrating the dependence of flexural strength on sintering temperature for Si₃N₄ and AlN sintered products according to the invention;

Fig. 4: a schematic for a device for polycondensation of organosilicon compounds in the formation of high molecular weight organosilicon compounds;

Figs. 5 and 6: plots illustrating the relationship between the number of impregnation treatments and flexural strength as well as effective density for Si₃N₄ and AlN sintered products according to the invention.

In the following examples, the data given are percentages by weight or parts by weight, unless specified otherwise.

Example 1

Dodecamethylcyclohexasilane was heat treated for 36 hours in an autoclave at 400°C in an argon atmosphere to obtain a resinous polycarbosilane with an average molecular weight of 800. Si₃N₄ powder with a grain size of less than 45 μm was worked up or ground together with 10 wt.-% (with respect to the Si₃N₄ powder) of the above polycarbosilane and a suitable amount of n-hexane. The mixture was pressed into prisms of 10 mm x 10 mm x 30 mm under a pressure of approximately 2000 kg/cm² and the prisms were heated in argon atmosphere at a temperature increase of 100°C/hour in such a way that the temperature at various stages in the range 800 to 1400°C was held constant for one hour. The dependence of flexural strength of the Si₃N₄ sintered products obtained at individual heating temperatures on sintering
temperature is shown in Fig. 2. As the figure shows, Si$_3$N$_4$ sintered products of sufficient strength can already be obtained at the relatively low temperature of 1000°C.

**Example 2**

Dodecamethylcyclohexasilane was heat treated for 36 hours in an autoclave at 400°C in an argon atmosphere to obtain a resinous polycarbosilane with an average molecular weight of 800. AlN powder with a grain size of less than 45 μ was worked up or ground together with 10 wt.-% (with respect to the AlN powder) of the above polycarbosilane and a suitable amount of n-hexane. The mixture was pressed into prisms of 10 mm x 10 mm x 30 mm under a pressure of approximately 2000 kg/cm$^2$ and the prisms were heated in a nitrogen atmosphere at a temperature increase of 100°C/hour in such a way that the temperature at various stages in the range 800 to 1400°C was held constant for one hour. The relationship between the flexural strength of the resulting AlN sintered products and the sintering temperature is shown in Fig. 3. As the figure shows, sintered products of sufficient strength can be obtained at a temperature as low as 1100°C, according to the invention.

**Example 3**

Linear dimethylpolysilane produced from dimethyldichlorosilane was placed in an autoclave and heated for 32 hours in an argon atmosphere at 30 atm. to a temperature of 410°C to obtain polycarbosilane with an average molecular weight of 1600. Si$_3$N$_4$ powder with an average grain size of 2 μ was worked up or ground together with 10 wt.-% (with respect to the Si$_3$N$_4$ powder) of the above polycarbosilane as binding agent. The mixture was placed in a graphite mold to form prisms of 10 mm x 10 mm x 30 mm and heated by means of high frequency induction heating at a temperature increase of 300°C/hour in argon atmosphere under a pressure of 300 kg/cm$^2$ with the use of a hot-press. The temperature at various stages in the range 600 to 1600°C was held constant for 0.5 hours. Properties of the Si$_3$N$_4$ sintered product obtained at 1500°C are shown in Table 1.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Si$_3$N$_4$-10%MgO*: (1850°C hot pressed) conventional product</th>
<th>Si$_3$N$_4$-SiC hot-pressed example 3</th>
<th>Si N$_4$-SiC sintered product example 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>effective density (g/cm$^3$)</td>
<td>3.17</td>
<td>2.7 - 3.05</td>
<td>2.5 - 2.9</td>
</tr>
<tr>
<td>growth due to oxidation (mg/cm$^3$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000°C</td>
<td>7.3 (50 Std)</td>
<td>2.0 (50 Std)</td>
<td>4.0 (50 Std)</td>
</tr>
<tr>
<td>1200°C</td>
<td>5.2 (50 Std)</td>
<td>2.0 (50 Std)</td>
<td>4.0 (50 Std)</td>
</tr>
<tr>
<td>flexural strength (Kg/mm$^2$)</td>
<td>60-85</td>
<td>40-130</td>
<td>30-60 impregnation treatment 5 tires</td>
</tr>
<tr>
<td>Young's modulus (Kg/mm$^2$)</td>
<td>2.8x10$^4$</td>
<td>4.1x10$^4$</td>
<td>3.1x10$^4$</td>
</tr>
<tr>
<td>thermal shock resistance rapid heating, quenched (25°C ± 1000°C)</td>
<td>good</td>
<td>&gt;1000 cycles</td>
<td>&gt;1000 cycles</td>
</tr>
<tr>
<td>corrosion resistance in molten Al</td>
<td>good</td>
<td>very good</td>
<td>good</td>
</tr>
<tr>
<td>alkali resistance developed amount NH$_3$ in 25% NaOH</td>
<td>low</td>
<td>very low</td>
<td>low</td>
</tr>
<tr>
<td>hardness (Mohs)</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

*published values
Example 4

Linear dimethylpolysilane produced from dimethyldichlorosilane was placed in an autoclave and heated to 400°C for 30 hours under 30 atm. argon to produce polycarbosilane with an average molecular weight of 1500. AlN powder with an average grain size of 2 μm was worked up or ground with 10 wt.% (with respect to the AlN powder) of the above polycarbosilane as binding agent. The resulting mixture was placed in a graphite mold to form prisms of 10 mm x 10 mm x 30 mm and heated by means of a hot-press with a temperature increase of 300°C/hours under a pressure of 300 kg/cm² in an argon atmosphere. The temperature at various stages in the range 600 to 1700°C was held constant for 0.5 hours. Properties of the AlN sintered product obtained at 1500°C are listed in Table 2.
<table>
<thead>
<tr>
<th>Sample properties</th>
<th>AaN-20%Y₂O₃ (1700°C conventional sintered product)</th>
<th>AaN-SiC (hot-pressed) example 4</th>
<th>AaN-SiC molded sintered product example 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective density (g/cm³)</td>
<td>3.26-3.50</td>
<td>2.75-3.10</td>
<td>2.6-2.9</td>
</tr>
<tr>
<td>Growth due to oxidation (mg/cm²)</td>
<td>0.20 (72 Std)</td>
<td>0.5 (50 Std)</td>
<td>1.0 (50 Std)</td>
</tr>
<tr>
<td>1000°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1100°C</td>
<td>0.50 (72 Std)</td>
<td>1.0 (50 Std)</td>
<td>2.0 (50 Std)</td>
</tr>
<tr>
<td>Flexural strength (Kg/mm²)</td>
<td>30-70</td>
<td>15-80</td>
<td>30-50 impregnation treatment five times</td>
</tr>
<tr>
<td>Young's modulus (Kg/mm²)</td>
<td>3.1x10⁶</td>
<td>4.0x10⁶</td>
<td>3.5x10⁶</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (x10⁻⁶/°C)</td>
<td>5.70</td>
<td>4.86</td>
<td>5.54</td>
</tr>
<tr>
<td>25-1000°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal shock resistance rapid heating, quenched (25°C+1000°C)</td>
<td>good</td>
<td>&gt;1000 cycles</td>
<td>&gt;1000 cycles</td>
</tr>
<tr>
<td>Corrosion resistance in molten Al</td>
<td>good</td>
<td>very good</td>
<td>good</td>
</tr>
<tr>
<td>Hardness (Mohs)</td>
<td>7</td>
<td>7-8</td>
<td>7-8</td>
</tr>
</tbody>
</table>

*published values*
As can be seen from Table 2, sintered products having a density practically equal to the theoretical density can be obtained at temperatures as low as 1500°C according to the invention.

Example 5

The Si₃N₄ sintered product obtained by sintering at 1100°C according to Example 1, with an effective density of 2.31 g/cm³, was treated with a solution of 20 ml liquid polycarbosilane in 10 ml toluene under reduced pressure to impregnate the sintered product. The impregnated sintered product was heated to 1100°C in 8 hours in an argon atmosphere, resulting in a new or treated sintered product. The effective density of this Si₃N₄ sintered product was 2.41 g/cm³. This product was subjected to consecutive impregnation treatments and heating stages under the same conditions as described above. The effective density of the resultant sintered product increased to 2.48 g/cm³. When the sintered product formed in this way was again subjected to the subsequent treatment under the same conditions as described above, the effective density of the product attained a value of 2.54 g/cm³. By repeating the impregnation and heating procedures as described above, sintered products of high strength can be obtained even at low sintering temperatures. The relationship between the number of impregnations and flexural strength or effective density of products obtained according to this example is shown in Fig. 5.

Example 6

AlN sintered products obtained by sintering at 1100°C according to Example 2 were placed in an autoclave together with the polycarbosilane and the pressure in the autoclave was reduced. The temperature was increased to 400°C to impregnate the sintered product with the polycarbosilane, and pressure was simultaneously applied using nitrogen gas. The impregnated sintered product was then heated to 1100°C in 8 hours in the nitrogen atmosphere to obtain a new sintered product. The above impregnation and heating procedures were repeated. The relationship between number of impregnations and flexural strength or effective density for the products obtained according to this example is shown in Fig. 6.
Example 7

A solution of 3 g octaphenyltrisilane \((\text{C}_6\text{H}_5)_3\text{SiSi(C}_6\text{H}_5)_2\text{Si(C}_6\text{H}_5)_3\) in benzene and 30 g \(\text{Si}_3\text{N}_4\) powder of grain size 45 \(\mu\) was thoroughly worked up or ground and the resulting mixture was pressed into a prism 10 mm x 10 mm x 30 mm under a pressure of 1000 kg/cm\(^2\). The formed prism was heated in a nitrogen atmosphere to 1300°C at a temperature increase of 100°C/hour to obtain a sintered product with an effective density of 2.25 g/cm\(^3\). The resulting product was heated in air for 3 hours to 900°C. The \(\text{Si}_3\text{N}_4\) sintered product obtained in this way had a free carbon content of less than 0.2% and an effective density of 2.27 g/cm\(^3\). The flexural strength of the product was 6.3 kg/mm\(^2\).

Example 8

A solution of 4 g p-bis(dimethylvinylsilyl)benzene \((\text{CH}_2=\text{CHSi(CH}_3)_2-\text{C}_6\text{H}_4\text{Si(CH}_3)_2\text{CH=CH}_2)\) in xylene and 30 g AlN powder with a grain size less than 45 \(\mu\) was thoroughly ground and the resulting mixture was pressed to form a prism 10 mm x 10 mm x 30 mm under a pressure of 700 kg/cm\(^2\). The prism was heated to 1200°C in a nitrogen atmosphere in 12 hours. The final sintered product had an effective density of 2.30 g/cm\(^3\) and a flexural strength of 6.4 kg/mm\(^2\).

Example 9

p-bis(oxymethylsilyl)benzene

was heated and polymerized in the presence of a potassium hydroxide catalyst to form high molecular weight organosilicon compounds with an average molecular weight of 5000. A solution of 4 g of the high molecular weight organosilicon compound in benzene and 500 g \(\text{Si}_3\text{N}_4\) powder with a grain size less than 45 \(\mu\) was thoroughly worked up or ground and the resulting mixture was pressed to form a prism 10 mm x 10 mm x 30 mm under a pressure of 700 kg/cm\(^2\). The prism was then heated to 1400°C in an argon atmosphere at a temperature increase of 100°C/hour to obtain a sintered product with an effective density of 2.20 g/cm\(^3\).
The Si₃N₄ sintered product, together with the above high molecular weight organosilicon compound, was placed in an autoclave and the pressure was reduced. The temperature was increased to 400°C to impregnate the sintered product with the high molecular weight organosilicon compound (until a pressure of 15 atm. was attained). The impregnated sintered product was then heated to 1400°C in an argon atmosphere at a temperature increase of 100°C/hour. The resulting sintered product had an effective density of 2.35 g/cm³ and a flexural strength of 11 kg/mm².

Example 10

A mixture of about 78% dimethyldichlorosilane, 8% methyltrichlorosilane, 3% trimethylchlorosilane and 2% methyldichlorosilane, synthesized directly from methylene chloride and metallic silicon, was polycondensated using the apparatus shown in Fig. 4.

The mixture described above, together with argon, was fed into a reaction column 2 heated at 750°C at a rate of 1 l/hour. In the reaction column 2, the starting materials were subjected to a decomposition and polycondensation reaction to form a high molecular weight compound and a low molecular weight compound. A portion of the high molecular weight polymer can be removed from the reaction column 2, but the majority of the high molecular weight compound was fed into a fractionating column 5 together with the low molecular weight compound, where the high molecular weight compound was separated from gas and the low molecular weight compound. The low molecular weight compound was recycled into the reaction column 2 and used again as a starting material. The yield of high molecular weight compound was 19% and the average molecular weight was 1800. The high molecular weight compound obtained in liquid form was thoroughly worked up or ground with Si₃N₄ powder of grain size less than 45 μ in a nitrogen atmosphere, in an amount corresponding to 10% by weight liquid high molecular weight compound. The resulting mixture was pressed to form a prism 10 mm x 10 mm x 30 mm under a pressure of 1000 kg/cm². The prism was heated to 1400°C at a rate of 100°C/hour to obtain a sintered product with an effective density of 2.25 g/cm³ and a flexural strength of 8 kg/mm².

Even though the invention has been described above using Si₃N₄ and AlN as typical examples of the well known nitrides, other metal nitrides
can also be used, according to the invention, to obtain sintered products with equally excellent properties.

According to the invention, a process is presented for the production of sintered products with excellent mechanical strength, thermal resistance, oxidation resistance, corrosion resistance and thermal shock resistance at lower sintering temperatures than those used in conventional processes by using organosilicon compounds or high molecular weight organosilicon compounds as binding agents for the nitrides. The nitride sintered products obtained according to the invention can be used to exhibit these excellent properties in many areas which require high thermal stability, oxidation resistance, corrosion resistance and mechanical strength, as well as in all applications where nitride sintered products have already been used, such as, for example, melting crucibles, blast furnace materials, tubes, nozzles, turbine blades, diverse engine parts, coating materials, nuclear reactor materials, etc.
FIG. 1

Temperature (°C)

Residual weight (%)
Sintering Temperature (°C)

**FIG. 2**

Flexural Strength kg/mm²
FIG. 3

Flexural Strength kg/mm²

Sintering Temperature (°C)
FIG. 5

Number of Impregnations

Flexural Strength $\text{kg/mm}^2$

Effective Density $\text{g/cm}^3$
FIG. 6

Flexural Strength kg/mm²

Effective density g/cm³

→ Number of Impregnations