

**FIBER REINFORCED CERAMIC MATRIX
COMPOSITE PISTON AND CYLINDER/SLEEVE
FOR AN INTERNAL COMBUSTION ENGINE**

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BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION:

This invention relates to components of internal combustion engines and, more particularly, to a piston and cylinder/sleeve pair for an internal combustion engine made by the steps of, forming a piston of a structural fiber reinforced ceramic matrix composite material; applying a first erosion-resistant material on the skirt portion of the piston; forming a cylinder/sleeve of a structural fiber reinforced ceramic matrix composite material; and, applying a second erosion-resistant material on a cylinder wall, internal surface of the cylinder/sleeve.

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BACKGROUND ART:

In a classical prior art internal combustion engine 10 as depicted in a simplified drawing of Figure 1, the cylinders 12 and pistons 14 are of metal. Early engines were of cast iron while later engines are of lighter metals and alloys of, for example, aluminum. The use of a cylindrical sleeve insert 16 for the walls of the cylinders became common in aluminum engine blocks and diesel engine blocks. In traditional cast iron engine blocks, once wear occurred within the engine, the cylinders had to be bored and honed and then oversized pistons and rings used in the rebuilt engine. With the inserts, to rebuild an engine, if ever necessary, the sleeve inserts 16 need only be replaced. Regardless of the materials used for the cylinder walls, the standard method of sealing the space between the cylinder walls and the piston is the piston ring. A space exists (and must exist) because of dissimilar thermal expansion of the piston and cylinder sleeve. If the piston and cylinder were sized exactly with only enough clearance for the piston to fit within the cylinder with a thin coating of lubricating oil film between them, as soon as the metal heated from the combustion within the cylinders and expanded, the piston would seize within the cylinder. If

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enough clearance were provided initially to allow for expansion, the blow-by would be so extreme that the engine would not run sufficiently to get up to temperature and create the proper seal. Thus, the expansion space is provided and the clearance gap is closed with piston rings. Each piston ring is disposed in a ring groove in the peripheral surface of the
5 piston adjacent the top thereof. Note also that the piston rings ride within the cylinder 12 or sleeve insert 16 on a film of oil. If the oil is removed, the piston 14 will seize. While engine designs and materials have certainly improved over the years, there still remain deficiencies such as lower than desirable fuel efficiency and higher than desirable pollution emissions.

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Wherefore, it is an object of this invention to provide pistons and cylinders/sleeves for an internal combustion engine which are of maximum strength and durability and minimum weight for their size.

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It is another object of this invention to provide pistons and cylinders/sleeves for an internal combustion engine which are able to operate with reduced oil lubrication without damage.

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It is still another object of this invention to provide pistons and cylinders/sleeves for an internal combustion engine which are of materials which are non-eroding and self-lubricating to the degree necessary when in sliding contact with one another.

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It is yet another object of this invention to provide pistons and cylinders/sleeves for an internal combustion engine which have low and tailorable coefficients of thermal expansion.

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Other objects and benefits of this invention will become apparent from the description which follows hereinafter when read in conjunction with the drawing figures which accompany it.

DISCLOSURE OF THE INVENTION

The foregoing objects have been achieved by the ceramic piston and cylinder/sleeve pair for an internal combustion engine of the present invention comprising, a piston formed of a structural fiber reinforced ceramic matrix composite material; a first erosion-resistant material disposed on the skirt portion of the piston; a cylinder/sleeve formed of a structural fiber reinforced ceramic matrix composite material; and, a second erosion-resistant material disposed on a cylinder wall, internal surface of the cylinder/sleeve, the second erosion-resistant material also exhibits self-lubricating nature when in contact with the first erosion coating.

The preferred structural fiber reinforced ceramic matrix composite material comprises fibers of a generic fiber system disposed in polymer-derived ceramic resin in its ceramic state.

Additionally for light-weight coupled with strength, the fibers are tightly compressed within the polymer-derived ceramic resin to create between a 30% and 60% fiber volume.

Preferably, the first erosion-resistant material is comprised of mullite, or alumina, with TiO_2 and a metallic element, such as, but not limited to gold, silver, molybdenum or copper. Additionally, Tungsten carbide and alloys thereof have been demonstrated as suitable piston ring coatings.

Also preferably, the second erosion-resistant material comprises a mixture of alumina, TiO_2 , yttria, and a metallic element such as, but limited to, gold, silver, molybdenum or copper.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a simplified, partially cutaway drawing of a prior art cylinder and piston of an internal combustion engine.

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Figure 2 is an enlarged, simplified, partially cutaway drawing of a cylinder and piston of an internal combustion engine according to the present invention.

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BEST MODES FOR CARRYING OUT THE INVENTION

The inventors of the present invention have developed a new internal combustion engine design employing an improved structural fiber reinforced ceramic matrix composite (FRCMC) material providing a high temperature and high breakage resistance.

- 15 Essentially, all the surfaces exposed to combustion have a ceramic construction. This ceramic construction allows the wall surfaces adjacent to the combustion gases to operated at higher temperatures than prior art metal engines for increased fuel efficiency and decreased pollutant production. In addition, the ceramic construction does not employ the prior art monolithic ceramic material sometimes used in internal combustion engines.
- 20 Instead, the engine employs structural fiber reinforced ceramic matrix composite (FRCMC) materials of a kind known in the art. It should be noted, however, that FRCMC materials are quite new and heretofore have been employed only for structural uses such as aircraft hot structure and the like. Nowhere in the prior art or literature associated with the FRCMC materials as provided by the manufacturer thereof is it taught or suggested that these
- 25 materials could be employed in an internal combustion engine. In particular, there is no belief in the art that FRCMC materials can be used in sliding contact with one another because of their observed tendency to quickly self-destruct when rubbed together. Also, ceramic materials made according to prior art techniques are strain intolerant and notch sensitive, thus inhibiting successful rate manufacturability.

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Engine parts made from an improved FRCMC material as developed by the inventors of the present invention are not susceptible to the stain limitations and notch sensitivity that would be experienced by such part made of conventional FRCMC materials. This improved FRCMC material employs either of two pre-ceramic resins or a modified
5 cementatous resin which emulates processing techniques of polymer composites which are commercially available such as silicon-carboxyl resin (sold by Allied Signal under the trade name Blackglas), alumina silicate resin (sold by Applied Poleramics under the product designation C02) or monoaluminum phosphate (also known as monoaluminum phosphate) resin, combined with a generic fiber system such as, but not limited to, alumina,
10 Nextel 312, Nextel 440, Nextel 510, Nextel 550, silicon nitride, silicon carbide, HPZ, graphite, carbon, and peat. To accomplish the objectives of the invention, the fiber system is first coated to a few microns thickness with an interface material such as, but not limited to, carbon, silicon nitride, silicon carbide, and boron nitride, or multiple layers of one or more of these interfacial materials. The interface material prevents the resin from adhering
15 directly to the fibers of the fiber system. Thus, when the resin has been converted into a ceramic, there is a weak disbond layer between the ceramic matrix and the fibers imparting the desired breakage resistant qualities to the final FRCMC. Hereinafter, the term polymer-derived ceramic resin or matrix is defined to include both true pre-ceramic polymer systems and cementatous systems that have been modified to emulate the processing
20 methods of typical structural polymer composite systems.

The method of forming a breakage-resistant engine part from structural FRCMC materials generally entails the steps of applying the interface material to the fiber system, mixing the interface coated fiber system with the resin, forming the resin containing the
25 coated fibers into a desired part, and firing the resultant part at a temperature and for a time which converts the resin to a ceramic.

As is well known and understood by those of ordinary skill in the art, a closer fit between pistons and cylinders of an internal combustion engine means less chance of
30 blow-by and cold start pollutant emissions. On the other hand, a closer fit means more

opportunity for engine seizure. Since engine seizure is such a major and costly calamity, designers typically opt for minimizing and hopefully eliminating the chance of seizure in favor of lowering operating efficiencies. However, the pistons and cylinder/sleeves made of the above-described FRCMC material can withstand much higher operating

5 temperatures than convention internal combustion engines. The higher temperatures provide for more complete burning of the fuel which, in turn, leads to greater fuel efficiency and lower unburned pollutants being produced. Moreover, since the coefficient of thermal expansion of the FRCMC parts is much lower than metals, much closer tolerances can be maintained without the danger of engine seizure, further adding to the foregoing benefits.

10 If the coefficient of thermal expansion of pistons and cylinders could be reduced to a minimum and/or tailored to result in virtually identical thermal expansion of the piston and cylinder bore (at peak and typical operating temperatures), the tolerances could be maintained even closer for added benefits without increasing the danger of seizing, breaking, and/or cracking.

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The above-described FRCMC material employed in the engine would be harder than steel, while being lighter than aluminum. The materials can be operated as a piston or sleeve material at bulk material temperatures in excess of 1200°F. This enhanced temperature capability combined with fatigue and creep resistance superior to steel pistons

20 (at these same temperatures) will result in increased durability and performance. Additionally, being a ceramic, it is not prone to the oxidation problems of metal.

The pistons and cylinders/sleeves of the present invention attain the stated objectives by use of the above-described FRCMC material in a particular manner and with

25 additional additives. The elements of the present invention are depicted in Figure 2. There is an all "ceramic" piston 18 which has the wrist-pin 22 connected to the connecting rod 24. The piston 18 includes ring grooves 26 and a "skirt" 28. The above-described FRCMC material is used where wear and thermal resistance are a problem or where enhanced thermal resistance and wear are desired to achieve increased performance or

30 reduced emissions, and metal is used where application requirements demand strength

with no high temperature or elevated heat load requirements (piston rods for example). Thus, there is also a FRCMC cylinder/sleeve 30 carried by a metal engine "block" 32. The designation "cylinder/sleeve" is employed rather than "cylinder" or "sleeve" since a cylinder is typically part of the engine block itself and a sleeve is a thin cylindrical liner disposed as the sidewalls of a cylindrical cylinder. In this case, in one engine design employing the present invention, the FRCMC cylinder/sleeve 30 may be a thin sleeve within a cylinder of the block 32 inserted strictly for insulation and wear resistance, while in another it may be thick enough to comprise a structural, load carrier integral component of the surrounding engine block, not merely supported and carried by the surrounding block

10 32.

Since the piston 18 takes the force of combustion and transmits that force to the crankshaft through the connecting rod 24, it can be subjected to more forces tending to break it than many other parts internal to the engine. Since inertia is a factor in engine life, wear, and fuel efficiency, having the lightest piston possible with the maximum strength is desirable. It is also desirable for overall vehicle fuel efficiency to have the engine (and therefore the cylinder/sleeve 30) be as strong and lightweight as possible. This can be addressed for purposes of the present invention in several ways. The first is the manner of constructing the piston 18 and cylinder/sleeve 30.

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A FRCMC behaves substantially like any other composite material such as so-called "fiberglass". That is, the manner in which it is constructed has a direct bearing on the ultimate weight and strength of the part. For example, fiberglass comprises glass fibers disposed throughout a hardened resin material such as epoxy. The higher the resin-to-fiber ratio in the end product, the heavier the product is and the more breakage prone the product is. By using only enough resin to bond tightly packed fibers together, the resultant product is light weight, strong, and tough. A fiberglass fishing pole is a good example. The length and orientation of the fibers themselves also contribute to the qualities of the product. To add bulk and overall strength to a fiberglass shell (as in a hot tub or the like) a so-called "chop gun" is used to blow a mixture of short, random oriented glass fibers onto

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a surface. By contrast, to make a strong, lightweight, flexible boat hull, woven glass fiber cloth matting is layed-up in a mold and the resin is rolled and pressed into the fibers making a dense composite. Even stronger and more lightweight materials can be made by laying up the fiberglass materials and subjecting them to a squeezing pressure so as to
5 tightly compact them prior to the setting up of the resin.

In the preferred construction of the parts addressed by the present invention, the resin/fiber mixture is formed by a combination of heat and pressure by methods well-known by those experienced in the art of manufacturing military aircraft structural composites.
10 The formed pre-ceramic composites are then subjected to a high temperature firing cycle (per material supplier specifications) to convert the pre-ceramic composite shape into a ceramic matrix composite structural part.

Having thus addressed the aspect of making the parts lightweight and strong, the
15 issue of self-lubrication/erosion-resistance will now be addressed. The contacting surfaces of the cylinder/sleeve 30 and the piston skirt 28 are treated differently. In a co-pending application entitled REDUCING WEAR BETWEEN STRUCTURAL FIBER REINFORCED CERAMIC MATRIX COMPOSITE AUTOMOTIVE ENGINE PARTS IN SLIDING CONTACTING RELATIONSHIP, Serial Number _____, filed on even date
20 herewith, the use of an erosion-resistant material on the surface of the structural FRCMC is disclosed. Specifically, it was disclosed that:

The contacting surfaces of a structural FRCMC component are covered with an erosion-resistant coating which bonds tightly to the wearing surface of the component. For
25 this purpose, the erosion-resistant coating preferably comprises mullite (i.e. alumina silicate Al_2Si_4), alumina (i.e. Al_2O_3), or equivalent materials, applied via a plasma spray generally according to techniques well known to those of ordinary skill in the art.

The erosion-resistant coating is applied as follows. Prior to the application of the
30 erosion-resistant coating, all holes for spark plugs, valves, wrist pins, etc. are machined.

Commercial grade diamond cutting tools are recommended for this purpose. Any other machining as described later is also done at this point. Upon the completion of the machining processes, if any, all sharp edges on the surface of the part are knocked down using diamond paper.

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If the part has been machined, it is placed in an oven for a time and temperature adequate to assure "burn off" of any of the cutting lubricants used in the machining process. (Typically 2Hrs @ 700°F, but is lubricant dependent.)

- 10 The key is getting the erosion-resistant coating to bond to the FRCMC structure. If the surface of the FRCMC structure is not properly prepared, the erosion-resistant coating can simply flake off and provide no long-term protection. In a preferred approach, the surface of the FRCMC structure is lightly grit-blasted to form small divots within the ceramic matrix of the FRCMC structure. It is also believed that the light grit blasting
- 15 exposes hairs or whiskers on the exposed fiber of the generic fiber system which the erosion-resistant coating can grip and adhere thereto. Typical grit blasting that has proved successful is 100 grit @ 20 PSI.

- According to a second possible approach, the surface of the FRCMC structure can
- 20 be provided with a series of thin, shallow, regularly-spaced grooves similar to fine "threads" of a nut or bolt, which the erosion-resistant coating can mechanical lock into. Essentially, the surface is scored to provide a roughened surface instead of a smooth surface. The depth, width, and spacing of the grooves is not critical and can be determined for each part or component without undue experimentation. In general, the grooves should be closely
- 25 spaced so as to minimize any large smooth areas of the surface where there is a potential for the erosion-resistant coating to lose its adhesion and flake off. Thus, over-grooving would be preferable to under-grooving the surface with the exception that over-grooving requires the application of additional wear material to provide a smooth wear surface after final grinding. The grooves should be shallow so as to provide a mechanical locking area

for the erosion-resistant coating without reducing the structural strength of the underlying FRCMC structure to any appreciable degree.

After surface preparation, the part is cleaned by using clean dry compressed air
5 and then loaded in an appropriate holding fixture for the plasma spray process. Direct air blowers are used to cool the opposite side of the part during the application of the erosion-resistant coating.

The plasma sprayed erosion-resistant coating is then applied using a deposition
10 rate set to 5 grams per minute or more. The holding fixture speed, plasma gun movement rate across the surface, and spray width are set to achieve a barber pole spray pattern with 50% overlap. The spray gun is set relative to the sprayed surface from 0.1 inches to 3 inches away. Particle sizes used for this process range from 170 to 400 mesh. Enough material is applied to allow for finish machining.

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After the application of the erosion-resistant coating, the coated surface is smoothed out with diamond paper or an appropriate form tool (commercial grade diamond tools recommended) to achieve the final surface contour.

20 Additionally, the plasma sprayed coating can be applied and then the part with the erosion-resistant coating attached can be further reinfiltated with the pre-ceramic polymer resin and then converted to a ceramic state. The result is an additional toughening of the coating by essentially incorporating the coating into the mixed or combined ceramic matrix composite formed from the combination of the FRCMC and a ceramic matrix reinforced
25 monolithic wear coating integrally bound together by the common ceramic matrix. In an completely different approach according to the present invention, the erosion-resistant material in powder form may be dispersed within the matrix material prior to forming the component for improved wear resistance.

To meet the specific needs of the piston and cylinder/sleeve of the present invention, however, certain additional considerations must be made for preferred performance. The preferred erosion-resistant material for the wear surface of the cylinder/sleeve 30 is a coating mixture of alumina, between 2% and 29% TiO_2 , between 5 0% and 1% yttria and between 2% and 15% of molybdenum. The mixture is a powder which is plasma sprayed in the conventional manner as that known to those skilled in the art of plasma spraying. The mixture provides both erosion-resistance and self-lubricating qualities to the surface. As the sidewall is that against which the piston ring is going to slide, mullite (in place of the alumina) is optional but not preferred because it is softer than 10 the above mixture.

The preferred erosion-resistant material for the skirt of the piston 28 is a mixture of alumina or mullite and TiO_2 (between 2-15%) and molybdenum (between 2-15%). The skirt coating is designed to be softer than the sleeve coating.

Wherefore, having thus described the present invention, what is claimed is:

1. A ceramic piston and cylinder/sleeve pair for an internal combustion engine having low coefficients of thermal expansion comprising:
 - 5 a) a piston formed of a structural fiber reinforced ceramic matrix composite material;
 - b) a first erosion-resistant material disposed on the skirt portion of said piston, said first erosion-resistant material also possessing self-lubricating characteristics;
 - c) a cylinder/sleeve formed of said structural fiber reinforced ceramic
10 matrix composite material; and,
 - d) a second erosion-resistant material disposed on a cylinder wall surface of said cylinder/sleeve, said second erosion-resistant material also possessing self-lubricating characteristics and being harder than said first erosion-resistant material.
- 15 2. The ceramic piston and cylinder/sleeve pair of claim 1 wherein:
said structural fiber reinforced ceramic matrix composite material comprises fibers of a generic fiber system disposed in polymer-derived ceramic resin in its ceramic state.
- 20 3. The ceramic piston and cylinder/sleeve pair of claim 2 wherein:
said fibers are tightly compressed within said polymer-derived ceramic resin
4. The ceramic piston and cylinder/sleeve pair of claim 1 wherein:
said first erosion-resistant material comprises a mixture of alumina or
25 mullite, between 2% and 15% TiO_2 and between 2% and 15% molybdenum.
5. The ceramic piston and cylinder/sleeve pair of claim 1 wherein:
said second erosion-resistant material comprises a mixture of alumina,
between 2% and 29% TiO_2 , between 0% and 1% yttria and between 2% and 15%
30 molybdenum.



6. A method of making a ceramic piston and cylinder/sleeve pair having low coefficients of thermal expansion for use in an internal combustion engine comprising the steps of:

- 5 a) forming a piston of a structural fiber reinforced ceramic matrix composite material;
- b) applying a first erosion-resistant and self-lubricating material on a skirt portion of the piston;
- c) forming a cylinder/sleeve of the same structural fiber reinforced ceramic matrix composite material; and,
- 10 d) applying a second erosion-resistant and self-lubricating material which is harder than said first erosion-resistant and self-lubricating material on a cylinder wall surface of the cylinder/sleeve.

15 7. The method of claim 6 wherein said step of forming a piston of a structural fiber reinforced ceramic matrix composite material comprises the steps of:

- a) disposing fibers of a generic fiber system in the shape of a piston;
- b) impregnating the fibers with a polymer-derived ceramic resin;
- c) compressing the resin-impregnated fibers together; and,
- 20 d) firing the thus compressed, resin-impregnated fibers at a temperature and for a time associated with the resin which converts the resin into a ceramic.

8. The method of claim 6 wherein said step of forming a cylinder/sleeve of the same structural fiber reinforced ceramic matrix composite material comprises the steps of:

- 25 a) disposing fibers of a generic fiber system in the shape of a cylinder sleeve;
- b) impregnating the fibers with a polymer-derived ceramic resin;
- c) compressing the fibers together; and,



d) firing the thus compressed, resin-impregnated fibers at a temperature and for a time associated with the resin which converts the resin into a ceramic.

5 9. The method of claim 6 wherein said step of applying a first erosion-resistant and self-lubricating material on a skirt portion of the piston comprises:

 plasma spraying the skirt portion of the piston with a mixture of alumina or mullite, between 2% and 15% TiO_2 and between 2% and 15% molybdenum.

10 10. The method of claim 6 wherein said step of applying a second erosion-resistant and self-lubricating material on an internal cylinder wall surface of the cylinder/sleeve comprises:

 plasma spraying the wall surface of the cylinder/sleeve with a mixture of mullite or alumina, between 2% and 29% TiO_2 , between 0% and 1% yttria and between 2%
15 and 15% molybdenum.

 11. A method of making a ceramic piston and cylinder/sleeve pair having low coefficients of thermal expansion for use in an internal combustion engine comprising the steps of:

20 a) forming a piston of a structural fiber reinforced ceramic matrix composite material;

 b) plasma spraying a skirt portion of the piston with a first erosion-resistant and self-lubricating material comprising a mixture of alumina or mullite, between 2% and 15% TiO_2 and between 2% and 15% molybdenum;

25 c) forming a cylinder/sleeve of the same structural fiber reinforced ceramic matrix composite material; and,

 d) plasma spraying a wall surface of the cylinder/sleeve with a second erosion-resistant and self-lubricating material which is harder than said first erosion-resistant and self-lubricating material comprising a mixture of mullite or alumina, between
30 2% and 29% TiO_2 , between 0% and 1% yttria and between 2% and 15% molybdenum.



12. The method of claim 11 wherein said step of forming a piston of a structural fiber reinforced ceramic matrix composite material comprises the steps of:

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- a) disposing fibers of a generic fiber system in the shape of a piston;
 - b) impregnating the fibers with a polymer-derived ceramic resin;
 - c) compressing the resin-impregnated fibers together; and,
 - d) firing the thus compressed, resin-impregnated fibers at a temperature and for a time associated with the resin which converts the resin into a ceramic.

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13. The method of claim 11 wherein said step of forming a cylinder/sleeve of the same structural fiber reinforced ceramic matrix composite material comprises the steps of:

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- a) disposing fibers of a generic fiber system in the shape of a cylinder sleeve;
 - b) impregnating the fibers with a polymer-derived ceramic resin;
 - c) compressing the fibers together; and,
 - d) firing the thus compressed, resin-impregnated fibers at a temperature and for a time associated with the resin which converts the resin into a ceramic.

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14. A method of making a ceramic piston and cylinder/sleeve pair having low coefficients of thermal expansion for use in an internal combustion engine comprising the steps of:

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- a) forming a piston of a structural fiber reinforced ceramic matrix composite material;
 - b) applying a first erosion-resistant and self-lubricating material being a mixture of alumina or mullite, TiO_2 and a metal chosen from the group consisting of gold, silver, molybdenum, and copper on a skirt portion of the piston;
 - c) forming a cylinder/sleeve of the same structural fiber reinforced ceramic matrix composite material; and,
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d) applying a second erosion-resistant and self-lubricating material being a mixture of mullite or alumina, TiO_2 , yttria and a metal chosen from the group consisting of gold, silver, molybdenum, and copper on a cylinder wall surface of the cylinder/sleeve.

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15. The method of claim 14 wherein said step of applying a first erosion-resistant and self-lubricating material on a skirt portion of the piston comprises:
plasma spraying the skirt portion of the piston with a mixture of alumina or mullite, between 2% and 15% TiO_2 and between 2% and 15% molybdenum.

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16. The method of claim 14 wherein said step of applying a second erosion-resistant and self-lubricating material on an internal cylinder wall surface of the cylinder/sleeve comprises:

plasma spraying the wall surface of the cylinder/sleeve with a mixture of
15 mullite or alumina, between 2% and 29% TiO_2 , between 0% and 1% yttria and between 2% and 15% molybdenum.

