JOURNAL OF ENGINEERING APPLICATIONS
VOLUME 1, NUMBER 1 (1998)

CERAMIC ENGINES: MATERIAL PROPERTIES FOR HIGHER PERFORMANCE[1]

SIMOLOWO, O. E.[2]

ABSTRACT: The four-stroke reciprocating internal combustion engine has been used as a case study, being that commonly utilized in most automobiles. General properties of ceramics were discussed while exposure was given to some hihg-performance ceramics. Theoretical deduction and analysis were then carried out to show improved engine performance using ceramic components. The engine performance parameters considered are: (i) power output (ii) mean effective pressure (iii) speed of engine rotation and (iv) mechanical efficiency. Analysis based on ceramic properties showed that ceramics such as silicon carbide (SiC), silicon nitride (Si_3N_4), zirconia $(Zr\ O_2)$ and, titanium oxide $(Ti\ O_2)$ proved to have more favourable properties for most engine parts when subjected to engine conditions where they are located as compared to their metallic, steel and alloy counterparts. Though much work has been done in the production of ceramic engines, predictions as to developing (i) adiabatic ceramic engines and (ii) turbo compounded engines show the extent of work that still needs to be done in this area of developing ceramic engines.

1. INTRODUCTION:

Considerable research has been carried out on the production of engines having some of their components made of ceramic materials. There is, however, still the need for a better understanding as to how this area of ceramic technology can influence the automobile industry and even improve its final output. Such understanding can be attained through the analysis of the relations of engine performance parameters to properties of the ceramics used for the engine components. A follow-up based on the understanding of the possibilities of improved performance in automobile engines using ceramic components presents opportunities to open up ceramic- based automobile industries especially in the parts of the developing countries where the needed resources are available.

2. GENERAL PROPERTIES OF CERAMICS:

Ceramics are,generally, materials which are made up of non-metallic substance. They are basically oxides, carbides, and nitrides of non-metals. Examples are aluminium oxide $(A1_20_2)$, silicon carbide (Si C) and mullite $(3N_20_3.2\ Si\ 0_2)$. Tables I and II show the properties of different ceramics as compared to those of certain steel alloys used in engine manufacturing. Ceramics as compared to metal alloys are stronger in compression, brittle, chemically inert, good insulators, light-weight, and resistant to wear and corrosion. Ceramics also have higher melting points, lower coefficient of thermal expansion, better lubricity, higher useful temperature range and higher heat of capacity than metal alloys.

High-performance Ceramics: A number of ceramics which have been developed for use in specific manufacturing processes are known as high- performance ceramics. In the case of high-temperature automobile engine manufacturing, these ceramics include silicon nitride (Si_3N_4), silicon carbide (SiC), titanium oxide (TiO_2) and toughened zirconia (ZrO_2).

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[1] Suggestions for improving this study, made at an earlier departmental seminar, are acknowledged.

[2] Department of Mecchanical Engineering, University of Ibadan, Ibadan, Nigeria.

TABLE I: PROPERTIES OF VARIOUS CERAMICS

Material	Formula	M.P.(°C)	Specific Gravity (g/cm³)	Useful Temperature range (°C)	Thermal Conductivity (W/m°K) at	
					500°C	1000°C
Titanium oxide	TiO_2	1340	4.24	25-1100	3.8	3.3
Silicon carbide	SiC	3990	3.21	25-1300	22.5	23.7
Zirconia	ZrO_2	2677	5.90	25-1100	2.1	2.3
Silicon oxide	SiO_2	3999	2.20	25-1800	8.0	7.8
Zircon	$ZrO_2.SiO_2$	2340-2550	4.60	25-1100	4.3	4.1

TABLE II: PROPERTIES OF VARIOUS STEEL ALLOYS

AISI Type No.	410	403	414	416	418
Analysis %					
Chromium	11.5-13.5	11.5-13.0	11.5-13.5	12.0-14.0	12.0-14.0
Nickel	0.50 (max)	0.50 (max)	1.25-2.50	0.50 (max)	0.50 (max)
Carbon	0.15 (max)	0.15 (max)	0.15 (max)	0.15 (max)	0.15 (max)
Manganese	1.00 (max)	1.00 (max)	1.00 (max)	1.00 (max)	1.00 (max)
Silicon	1.00 (max)	1.00 (max)	1.00 (max)	1.00(max)	1.00 (max)
Melting Point (°C)	1482-1532	1432-1532	1427-1482	1482-1532	1454 -1482
Maximum Useful Temperature (°C)	704	704	676	676	704
Specific Gravity (g/cm³)	7.7	7.7	7.7	7.7	7.7

Silicon nitride and silicon carbide ceramics exceed the strength of steel alloys at high temperatures*[1]*. They also form protective layers of silicon oxide (SiO_2) under oxidising conditions and have useful temperature range of up to 1700°C to 2000°C depending on the oxidising atmosphere. Transformation - toughened zirconia has the property of blunting out micro-cracks that grow on it at temperatures below 1000°C *[2]*; it also has exceptionally good lubricity and is easily machined.

Most of the existing engine components discussed are made up of these high - performing ceramics with alterations in their compositions to suit their particular application.

3.ANALYSIS ON IMPROVING ENGINE PERFORMANCE: To improve the performance of an engine requires a good understanding of how the engine works. During the intake stroke of a fuel driven 4-stroke "RICE" engine, ari-fuel mixture fills volume $V_p + V_c$ at (B. D. C), where V_p = piston swept working volume and V_c= combustion volume. During compression stroke at TDC, piston compresses the mixture to volume V_c. The compression to V_c results in a rise in temperature. Ignition then takes place on the hot mixture by a spark from the spark plug. Subsequent explosion further raises the temperature of the mixture resulting in pressure rise in the volume V_c as the mixture tends to expand. This greatly increased pressure in V_c while piston is still at TDC is called "Firing pressure". In the power stroke that follows, the firing pressure thrusts the piston down from TDC to BDC while the pressure drops simutaneously. The volume now expands to $V_c + V_p$ in preparation for the exhaust stroke.

A plot of firing pressure against stroke is shown in Figures 1and 2 for four strokes. The mean effective pressure is deduced for all the strokes as shown for the power stroke. The mean effective pressure, P_m, is then made use of in preference to the general firing presssure.

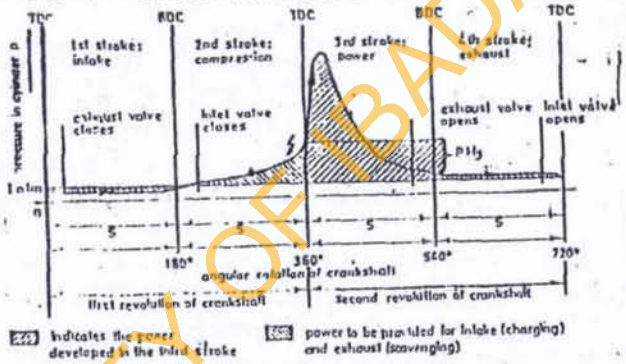

Fig. 1. Cylinder pressure diagram of a four-stroke engine.

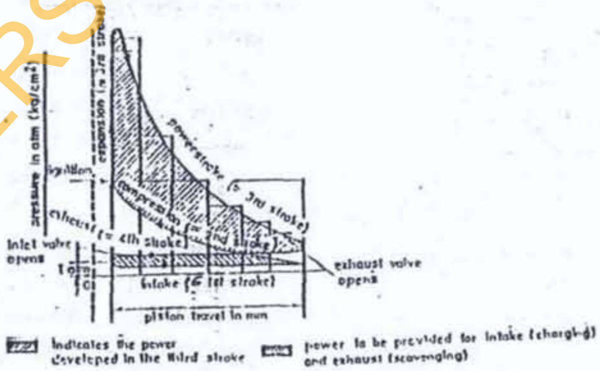

Fig. 2 . Cylinder pressure diagram (more usual four).

Since pressure needed to perform the three other strokes is obtained from the power stroke, the actual pressure that acts on the piston is the mean indicated pressure (P_{mi}) obtained where $P_{m1} = P_{m3} - (P_{m1} + P_{m2} + P_{m4})$.

In engine operation, P_{mi} produces a force converted to torque (T) about the axis of the crankshaft . $T = P_{mi} A(S/2)i = K_1 P_{mi} A(S)i = KP_{mi} V_T$ where i = number of cyliders, S = stroke = 2r, A = piston surface area, K_1, K = constants, and $V_T = A_p(S)i$ = total working volume of cyliders.
Power output P_o is given by K_2TN (N = rotational speed). i.e. $P_o = KP_{mi} V_T N$.
This expression for power output shows its dependence on mean effective pressure (P_{mi}), speed of rotation (N), cubic capacity (V_T) where K = 1/100 for 4-stroke cylinder engines *[3]*

3.1 HIGHER POWER OUTPUT: From the expression $P_o = K P_{mi} V_T N$, power output (P_o) is increased by increasing the indicated mean effective pressure (P_{mi}), the cubic capacity (V_T), and the engine rotational speed. More of relevance as to the use of other materials are the indicated mean effective pressure (P_{mi}) and engine speed (N).

3.2 INCREASING INDICATED MEAN EFFECTIVE PRESSURE (P_{Mi}): The volumetric efficiency n_v of an engine is given by $n_v = M_a/M_t$ where M_a = actual mass of air inducted into cylinder, and M_t = theoretical mass of air to fill piston-swept volume (V_P). Increasing the actual mass of mixture (M_a) raises the heat released during combustion thereby raising the pressure developed and the power output. Thus a higher mean effective pressure is obtained by increasing the volumetric efficiency (n_v).

In the process of charging the cylinder with fuel mixtures, oscillating conditions are developed in the inlet pipes due to the backward pressure created by the timely closing and opening of the inlet valve at high speeds.Optimum charging is achieved when the frequency of oscillation coincides with the opening and closing frequency of the valve. At this optimum charging condition the fuel-mixture flow is said to be resonance with the valve frequency. The attainment of resonance without hinderance in the inlet pipes and ducts is an indication of better volumetric efficiency.

Factors counteracting the development of resonance conditions are:

(i) The fuel vapour contained in purely metallic inlet pipes experiences condensation just on leaving the carburator. This makes the mixture heavy and less mobile.

(ii) The fuel mixture contained in the inlet duct situated in the cylinder head made of cast iron suffers over-heating, hence making the fuel mixture entering the cylinder very light and of low fuel efficiency.

(iii) Corrosion effects on the inlet pipes and ducts further contribute friction to the fuel flow by presenting rough surfaces to the mixture flow.

Improving fuel-mixture resonance by ceramic components: Extremely smooth ceramic inlet pipes and duct liners have better thermal insulating property and also have higher resistance to corrosion.These materials maintain the temperature of the mixture from carburator to the cylinders and hence a moderately dense mixture is a vailable for a more powerful combustion. Resonance is also aided by less frictional hinderance to its development in the corrosion-resisting ceramic.

Alternative to the use of ceramic in improving volumetric efficiency is a supercharged engine. However supercharging an engine increases the fuel cosumption per horsepower or the specific fuel consumption. Hence the use of ceramic material is preferrable in improving fuel-mixture resonance. The volumetric efficiency and the indicated mean effective pressure are thereby increased.

3.3 ADAPTING ENGINE FOR HIGHER SPEED OF ROTATION: The expression $P_o = K V_T N P_{mi}$ (obtained in section 3) is an indication that an increase in engine rotational speed (N) will increase power output (P_o). Howevever, a situation contrary to this is obtained in practice. An increase in engine speed (N) results in the following adverse effects:

(i) High inertia forces are developed by the reciprocating parts of the crank and valve mechanism causing damage.

(ii) Higher frictional losses are encountered in the cylinder due to increased piston speed.

(iii) The valves loose their conformity with the cam head at extremely high speeds. This is because the weights of the pistons, pushrod and tappets slow down the closing speed of the spring at very high speeds. Hence spring force is inadequate at high engine speeds.

(iv) Higher resistance is encountered in the inlet and exhaust systems thereby lowering the volumetric efficiency as well as power output.

Adaptations for higher rotational speed by ceramics: The use of ceramic components coupled with the method of cylinder splitting counteracts those adverse effects which result from high rotational speed. Cylinder liners, pistons, and ring made from suitable ceramic materials (Section 4) are much lighter,smoother and of higher operating temperatures than their steel counterparts. These components as a result of these properties develop less inertia forces at high speeds. Less friction is also encountered between the piston and cylinder liners at high temperatures since lubricity of these ceramics increases with temperature.

Valves and valve train components (tappets, pushrods) now made from suitable ceramic materials (Section 4) are lighter and run faster requiring a lower spring force. Conformity is therefore maintained between the valves and cam heads at high speeds.

Lower volumetric efficiency resulting at high speeds is also controlled by ceramic components as described in section 3.2.

3.4 HIGHER MECHANICAL EFFICIENCY: The power developed on the piston as a result of the indicated mean effective pressure is known as the indicated horse power (ihp). The part of this power that performs the function of overcoming friction is known as the friction horse power (fhp). The actual power left over, that gets to the output shaft, is known as the brake horse power (bhp)

Mechanical efficiency (n_m) is expressed as n_m = bhp/ihp, i.e. n_m = (ihp - fhp)/ihp; thus n_m = 1 - fhp/ihp. The final expression for mechanical efficiency (n_m) shows that an increase in the indicated horse power (ihp) or a decrease in the frictional horse power (fhp) will result in an increase of mechanical efficiency.

3.5 CERAMIC COMPONENTS FOR LOWER FRICTION HORSE-POWER: In section 3.2 the indicated mean effective pressure, and hence indicated horse-power, was increased by use of alternative ceramic components. This section will illustrate how mechanical efficiency can be further improved by reducing frictional horse-power.

The major sources of power loss in overcoming friction are as follows:

(i) Reciprocating action of the piston rings on the cylider liners.

(ii) Revolving movement of the crankshaft within the metal bearings, and

(iii) Rotational movements in various ball bearings used in driving accessories like radiator fan, water and oil pumps, etc.

Friction developed between piston rings and cylinder liners is reduced when the rings and the cylinder liners used are made from adequate ceramic materials (Section 4). Friction power is also minimised between metal bearings and crankshaft when ceramic metal bearings are used. All these ceramic components have an advantageous property of in creased lubricity at high temperature. Furthermore ceramic ball bearings made of silicon nitride are very smooth and usually last longer than the best steel bearings despite their brittleness. This is partly because their spherical geometry distributes the load over the surface, eliminating local concentration of stresses. All ceramic bearings of various forms used in engine parts, such as crankshaft and connecting rods, require less lubrication due to the good self-lubricating properties of ceramics at high temperatures.

A combination of all these ceramic components in an engine greatly reduces friction horse-power and also lowers the power input for lubrication. Hence mechanical efficiency is greatly increased.

4. RESULTS AND PERFORMANCE PREDICTIONS: Despite all the advantageous properties possessed by high performance ceramics, these ceramics are nevertheless comparatively brittle and of low ductile and thermal strength. Resstrictions are therefore made in their usage due to these unfavourable properties. Engine conditions to which these replacing ceramic components are subjected must not include very high impact loading, tensile stress and thermal stress. Table III shows some selected metallic components and their ceramic

TABLE III:CERAMIC COMPONENTS FOR HIGHER ENGINE PERFORMANCE

Engine Component (material)	Subjected Condition .	Alternative Ceramic Material.	Favourable Ceramic Properties.
Intake valve (chromium-nickel alloy), Exhaust valve.	High temperature (648°C - 1649°C).	Silicon carbide (SiC).	M.P. of 3999°C, useful range=1700°C, corossion resistant, forms SiO_2 under oxidation conditions.
Piston (aluminium, cast steel or iron).	High temperature (648°C -1649°C) Inertia forces.	Silicon nitride (Si_3N_4).	High useful temperature range20-1700°C, high strength at high temp.
Cylinder liners (gray cast iron), Rings.	High temperature wear.	Silicon carbide (SiC).	Low thermal conductivity, high resistance of wear, M.P. 3990°C.
Inlet ducts, Exhaust ducts (situated in case iron), Inlet (iron-carbon alloy).	Oscillation, resonance corrosion, condensation, overheating..	Zironia duct Liners and pipes.	High thermal insulation, resistance to corrosion, high surface smoothness.
Metal bearings (steel alloys).	Wear and abrasion.	Zirconia (ZrO_2).	Increasing lubricity at high temperatures, blunts micro-cracks.
Connecting rod (forged steel).	High inertia forces,high temperature impact loading and bending..	Titanium oxide (TiO_2).	Lighter and stronger than steel at high temperature, can withstand considerable impact load.
Teppets & pushrod (duralumin).	Compressive force, tensile forces, impact loading..	Titanium matrix (TiO_2).	Lighter and high strength at high temperature.
Anti-friction bearings (chromium steel).	High friction under direct load.	Silicon nitride (Si_3N_4).	

replacements.The engine conditions listed for the various components are those predominant conditions, amongst others, to which the components are subjected.

4.1.**PERFORMANCE PREDICTIONS:** The use of a particular ceramic component alters several performance parameters with one or two of these parameters being more prominently altered. The summary of all discussed in previous sections is presented in Table IV. This table shows which performance parameter is predominantly increased or altered by the use of several ceramic components.

TABLE IV :EFFECT OF CERAMIC COMPONENTS ON ENGINE PERFORMANCE

Ceramic component	Predominant Performance Parameters Directly Improved.
Silicon carbide intake and exhaust valves.	Higher rotational speed attainable.
Silicon nitride points	Lower inertia forces, higher engine speed
Silicon carbide clyinder liners and rings.	Lower friction horse - power, higher thermal efficiency.
Zirconia duct liners	Increased volumetric efficiency, relatively lower specific fuel conssumption.
Zirconia metal bearings	Lower friction horse-power, higher mechanical efficiency.
Titanium connecting rod	Lower inertia force, higher engine speed
Titanium tappets, pushrods and rocker arms	Lower spring force, higher engine speed
Silicon nitrate bearings	Lower friction horse-power, higher mechanical efficiency.

(i)Adiabtic ceramic engine: The use of ceramic pistons, cylinder liners, inlet and exhaust valves to improve thermal efficiency predicts the possibility of an adiabatic ceramic engine [1]. Combustion processes in an adiabatic ceramic engine is one with virtually no exchange of heat (Q) with the surrounding. From first law of thermodynamics. $Q_{12} = E_2 - E_1 + W_{12}$. For adiabatic processes $Q = 0$, thus, $E_2 - E_1 = -W_{12}$. This expression shows that work is done in the engine system ($W_{12} > 0$) at the expense of internal energy ($E_2 < E_1$). The thermal efficiency n_t, defined as n_t = work/heat supplied, becomes greatly increased since most of the internal energy in form of heat energy is derived from the heat supplied in the combustion chamber which is not lost to the surrounding. Adiabatic ceramic engines do not require any cooling system. The power that should be expended in driving radiator fan, pump and grill would be made available for the brake power, resulting in a higher mechanical efficiency.

(ii)Turbo-compounded ceramic engines: This type of engine when fully developed would be an improvement over the adiabatic ceramic engine. It will recover most of the thermal energy available at the exhaust pipe of the ceramic adiabatic engine. This engine improves engine power output, and fuel economy by translating the dynamic action of exhaust gases into kinetic energy using a ceramic turbine located in the engine exhaust system. The kinetic energy retrieved in the turbine is than transmitted through a gear train to produce torque in the crankshaft after great reduction ration.

(5)**CONCLUSION:** Despite existing high performance ceramics being used in engine manufacturing at present, much work is further needed for fool-proof production of ceramic engines. Ceramics that can withstand higher impact loading, and higher tensile and thermal stress must be developed. Ceramics that can transform at higher temperatures than that of zirconia are required for other engine parts within the combustion zone. Proper selection of areas in which ceramics are used in engines must be ensured to prevent failure. e.g. silicon carbide and silicon nitride components are used in areas of highest temperatures while zirconia components are able to withstand excessive abrasion and wear at temperatures lower than 100°C.

NOTATIONS

A = piston surface area
AISI = American Iron and Steel Institute
i = number of cylinders
k = constant dependent on number of cylinders
n = engine rotational speed
P_m = mean effective pressure
P_{mi} = indicated mean effective pressure
P_o = power output
r = crank radius
s = stroke
T = torque
V_C = combustion volume
V_P = piston-swept volume
V_T = total working volume of cylinders
n_m = mechanical efficiency
n_T = thermal efficiency
n_v = volumetric efficiency
BDC = bottom dead centre
TDC = top dead centre

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