Review on Ceramic Application in Automotive Turbocharged Engines

ALIAS Mohd Noor 1, a, MUHAMMAD RABIU Abbas 1, 2, b, SRITHAR Rajoo 1, c, MUHAMMAD HANAFI Md Sah 1, d and NORHAYATI Ahmad 3, e

1 UTM-Imperial Centre for Low Carbon Transportation Research Alliances, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia.
2 Dept. of Mechanical Engineering, Hassan Usman Katsina Polytechnic, P.M.B 2052, Katsina, Nigeria.
3 Dept. of Materials, Manufacturing and Industrial Engineering, Universiti Teknologi Malaysia.

a alias@mail.fkm.utm.my, b ibnabbas101@gmail.com, c srithar@fkm.utm.my, d m.hanafi@utm.my, e nhayati@fkm.utm.my

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Abstract. Research on the use of thermal barrier coatings in internal combustion engine had contributed in achieving higher thermal efficiency, improved combustion and reduced emissions of the engine. Low thermal conductivity ceramics can be used to control the temperature distribution and heat flow in high temperature structural components due to its inherent thermal insulation properties. For this reason much has been and is being done on the study and development of ceramics for use in automotive engine components working under severe temperature conditions and heavy loads due to their inherent thermal and mechanical properties. The objective of the study is to review the contributions of structural ceramics in the development and improvement of some of the major automotive engine components working under severe conditions of temperature. It is expected that the study will serve as a useful guide for the selection of materials which can withstand severe conditions of temperature and heavy loads for a novel turbocharger and turbocharged engine applications.

Introduction

The impoverish of fossil fuel resources, environmental concerns and economic competitiveness have necessitated the findings of more avenues to improve automotive engines efficiency and fuel conservation [1, 2]. In automotive applications, engines are required to have high specific power output as well as reduced pollutant emissions. These lead to the highly turbocharging of the current light and medium duty engines [3] which resulted in the improvement of the break mean effective pressure and enlarged the exhaust gas recirculation available zone [4, 5]. Turbocharging is the common technique of increasing power density of internal combustion engine. When used with the downsizing technique, turbocharging reduced the fuel consumption and pollution due to greenhouse gases [6, 7]. It is possible to increase the automotive engine specific power at constant rotational speeds or what is known as the engine downsizing, but the degradation of the transient performance of the engine restricts the benefits of downsizing [2]. Low fuel consumption can be achieved by having the correct ratio of the stoichiometric mixture in the cylinder which results to complete combustion of the gases present, thereby producing high exhaust gas temperatures [8]. When compared with a natural aspirated engine, turbocharged engine is smaller, lighter and more efficient due to less friction and pump losses as well as the lower inertia of the system [6]. The structure of the turbocharger is very complicated and its working environment is severe, that is why is the most easily breakdown component [9]. Furthermore, hot corrosion attack has become a major concern in a number of high temperature engineering applications [10]. To overcome the limitations of the traditional materials in meeting the challenges of the unrelenting demand of temperature increase for thermal efficiency improvement and prevent the high temperature degradation effects on
components, recent research efforts were concentrated towards the development and fabrication of thermal barrier coatings for the thermal insulation of components operating in severe temperature conditions [10]. Thermal barrier coating is a thin layer of material(s) having high insulating properties which are bonded to a metal substrate to insulate and protect it from temperature excursion or damage by foreign object. The application of thermal barrier coating can significantly improve the operating temperature capabilities, improve the efficiency, reliability and durability of a number of structural components operating under elevated temperature environments [11]. Ceramics are often more resistant to oxidation, corrosion and wear as well as being better thermal insulators than metals and their alloys, for this reason(s) ceramics are better, the most accepted and widely used materials for thermal barrier coatings [12]. Ceramics are the most thoroughly characterized materials and have become prime candidates for engineers and designers in a variety of wide range of applications which include heat exchangers, gas turbines, automotive engine components such as valves and tappets for cam followers, non-resonance knock sensors, spark plugs, piston crowns, cylinder liners, turbocharger turbine rotors and housings as well as other wear resistant components operating under elevated temperature environments [13-17]. The aim of this study is to review the contributions of ceramic thermal barrier coatings in improving the efficiency of some of the automotive internal combustion engine and turbocharger components operating under severe conditions of temperature.

**Ceramics for thermal barrier coatings**

Thermal barrier coating materials selection is restricted by some basic requirements such as high melting point, lower thermal conductivity, good adherence to substrate, chemical inertness, low sintering rate of porous microstructure, thermal expansion match with the substrate as well as absence of phase transformation between room and operation temperatures [12]. Hitherto, only few ceramic materials had been found to basically satisfy the above requirements and among these materials Yttria Stabilized Zirconia (YSZ) is the most widely studied and used thermal barrier coating material due to its best performance capabilities in high temperature applications such as diesel and gas turbine engines [12, 18-20]. Figure 1 shows an example of a zirconia ceramic coating on the engine cylinder of internal combustion engine. The advantages and disadvantages of other thermal barrier coating materials compared to Yttria Stabilized Zirconia are listed in table 1. Some of the established advantages of coating include an increase in the temperature capability of components, resistances to both erosion and corrosion, as well as the reduction of maintenance costs, thermal loads and high temperature oxidation of the components [21].

![Zirconia ceramic coating on engine cylinder](image_url)
Developments in advanced structural ceramics and their composite had opened a new chapter for the design and fabrication of mechanical structural components that can withstand severe conditions of temperature without serious changes to their mechanical properties. The development of these materials have no doubt contributed significantly to the improvement in the performance of high temperature engineering structural components without jeopardizing the environment, thereby making them to become more and more accepted for sophisticated technological applications due to their promising thermal and mechanical properties. Automotive vehicles which travel long distances have the problem of periodic replacement of worn parts. The use of ceramics as wear parts can solve this problem due to their excellent wear resistance, some tappets made of ceramics used for truck diesel engines are shown in figure 2 [16]. The knock sensor systems enable the efficient operation of the gasoline engines, figure 3 shows some knock sensors made of ceramics. Piezo ceramic material knock sensors can detect slight vibrations which occur prior to severe knocking [23].

Table 1 - Thermal Barrier Coating material and their characteristics [12].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>7-8 YSZ</td>
<td>(1) high thermal expansion coefficient</td>
<td>(1) sintering above 1473 K</td>
</tr>
<tr>
<td></td>
<td>(2) low thermal conductivity</td>
<td>(2) phase transformation (1443 K)</td>
</tr>
<tr>
<td></td>
<td>(3) high thermal shock resistance</td>
<td>(3) corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) oxygen-transparent</td>
</tr>
<tr>
<td>Mullite</td>
<td>(1) high corrosion-resistance</td>
<td>(1) crystallization (1023-1273 K)</td>
</tr>
<tr>
<td></td>
<td>(2) low thermal conductivity</td>
<td>(2) very low thermal expansion coefficient</td>
</tr>
<tr>
<td></td>
<td>(3) good thermal-shock resistance below 1273 K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4) not oxygen-transparent</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>(1) high corrosion-resistance</td>
<td>(1) phase transformation (1273 K)</td>
</tr>
<tr>
<td></td>
<td>(2) high hardness</td>
<td>(2) high thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>(3) not oxygen-transparent</td>
<td>(3) very low thermal expansion coefficient</td>
</tr>
<tr>
<td>YSZ+CeO₂</td>
<td>(1) high thermal expansion coefficient</td>
<td>(1) increased sintering rate</td>
</tr>
<tr>
<td></td>
<td>(2) low thermal conductivity</td>
<td>(2) CeO₂ precipitation (&gt; 1373 K)</td>
</tr>
<tr>
<td></td>
<td>(3) high corrosion-resistance</td>
<td>(3) CeO₂-loss during spraying</td>
</tr>
<tr>
<td></td>
<td>(4) less phase transformation between m and t than YSZ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5) high thermal-shock resistance</td>
<td></td>
</tr>
<tr>
<td>La₂Zr₂O₇</td>
<td>(1) very high thermal stability</td>
<td>(1) relatively low thermal expansion coefficient</td>
</tr>
<tr>
<td></td>
<td>(2) low thermal conductivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3) low sintering</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4) not oxygen-transparent</td>
<td></td>
</tr>
<tr>
<td>Silicates</td>
<td>(1) Cheap, readily available</td>
<td>(1) decomposition into ZrO₂ and SiO₂ during thermal spraying</td>
</tr>
<tr>
<td></td>
<td>(2) high corrosion-resistance</td>
<td>(2) very low thermal expansion coefficient</td>
</tr>
</tbody>
</table>
Ceramic thermal barrier coatings in turbocharged IC engine

The use of thermal barrier coatings in internal combustion engine has contributed in achieving higher thermal efficiency, improved combustion and reduced emissions of the engine. Low thermal conductivity ceramics can be used to control the temperature distribution and heat flow in high temperature structural components due to its inherent thermal insulation properties [24, 25]. The low heat rejection from combustion chamber as a result of the use of thermal barrier coating causes an increase in the available energy which increases the in-cylinder work and the amount of energy carried by the exhaust gases, as such can be utilized through turbocharging technology [26, 27]. Figure 4 shows how thermal barrier coating improves the engine efficiency of an internal combustion engine. Several works adopting ceramic thermal barrier coating on pistons, piston crowns, cylinder liner and head for achieving low heat rejection in internal combustion engine had existed [18, 28], figure 5 shows a demonstrated ceramic coated piston. Sekar and Kemo [29] developed an adiabatic engine for passenger car and reported performance improvement of 12%. Havstad et al.’s [30] work on a semi-adiabatic diesel engine had indicated up to 9% improvement on specific fuel consumption and about 30% reduction in in-cylinder heat rejection. On the other hand, Prasad et al. [31] used partially stabilized zirconia as thermal barrier coating material on piston crown face and reported a reduction of 19% in heat lost through the piston. In addition, Shrirao and Pawar [32] used mullite based thermal barrier coating on a turbocharged engine piston crown, cylinder head and valves and reported 12% increase in exhaust gas temperature, 21% increase in NOx as well as 20-28% reduction in carbon monoxide and hydrocarbon emission.

Automotive turbocharger

Turbocharger is like a small class of gas turbine consisting of the turbine and compressor sharing a single shaft and it is driven by the engine exhaust gases, turbochargers are intended to increase the
power of internal combustion engines. The first turbocharger was invented in the early twentieth century by Swiss engineer Alfred Buchi who introduced a prototype in order to increase the power of a diesel engine. At the time of its invention turbocharging was not widely accepted, but in the last few decades, turbocharging has become standard for most diesel and gasoline engines [34]. Turbocharger used the extracted energy of the engine exhaust gas by expanding it through the turbine which in turn drives the compressor by a shaft and compress ambient air into the engine air intake manifold. The normal air pressure is at 14.7 psi and there exist a limit to the pressure difference across the intake values in normal air aspirated engines which results in the limited air mass flow rate. The stoichiometric air/fuel ratio of the engine is 15:1, but with an increase in air flow rate lead to the alteration/disturbance of the equilibrium position of the air/fuel ratio. From Le Chatelier’s principle, more fuel will flow to maintain the equilibrium position and as such burning more fuel which as a result increases the power of the engine. Although the turbocharger consists of the turbine and compressor, it actually comprises with several working components, the turbine and the impeller are contained in their housings. It is possible to increase the automotive engine specific power at constant rotational speeds or what is known as the engine downsizing, but the degradation of the transient performance of the engine restricts the benefits of downsizing [2]. Therefore turbocharger design and performance have significant effect on the performance of the turbocharged engines [35].

**Turbocharger turbine volute design**

Automotive turbochargers used a small radial inflow turbine having a vaneless volute casing for the efficient delivery of the working fluid to the turbine rotor periphery. Whitfield and Noor [36] in their investigations had indicated that the design requirements for turbocharger turbine volute casing included its ability to collect the fluid, efficient fluid delivery to the turbine rotor as well as providing the desired rotor inlet conditions which lead to the design and identification of the flow conditions at the rotor inlet. Therefore the determination of the overall size of non-dimensional volute casing geometry, shape of the volute spiral flow path, the non-dimensional geometry variation of cross-sectional area with azimuth angle as well as the specification of the passage outer wall radius and cross-sectional area are the main procedures to be followed in the design of vaneless volute turbine casing of automotive turbocharger. Figures 6 and 7 show the free vortex assumptions with the ratios of centroid radius and cross-sectional area as a function of azimuth angle of the vaneless turbine volute respectively.

![Figure 6](image_url) - Centroid radius ratio as a function of azimuth angle with free vortex assumption [36]
Eq. 1 represents the radius ratio \( R_1/R_2 \) of an adiabatic modified free vortex relationship in terms of Mach numbers, \( M \) and flow angles, \( \alpha \) while Eq. 2 is the volute area ratio, \( A_1/A_2 \) as a function of inlet and discharge Mach numbers, \( M \), inlet and discharge flow angles as well as the stagnation pressure ratio \( P_{02}/P_{01} \) across the volute while \( \gamma \) is specific heat ratio.

\[
\frac{R_1}{R_2} = \frac{M_2 \sin \alpha_2}{S M_1 \sin \alpha_1} \left[ 1 + \frac{(\gamma - 1)/2 M_1^2}{1 + [(\gamma - 1)/2 M_2^2]} \right]^{\frac{1}{2}}. \tag{1}
\]

\[
\frac{A_1}{A_2} = \frac{M_2 \cos \alpha_2}{M_1 \sin \alpha_1} \left[ 1 + \frac{(\gamma - 1)/2 M_1^2}{1 + [(\gamma - 1)/2 M_2^2]} \right]^{-\frac{(\gamma + 1)}/[2(\gamma - 1)]} \frac{P_{02}}{P_{01}}. \tag{2}
\]

**Ceramic turbocharger rotors**

High mechanical strength is required for the automotive turbocharger rotor at high temperatures because it is not only subjected to high centrifugal force as a result of the high rotating speed but also it is subjected to a high thermal stress due to its exposure to high exhaust gas temperatures. Turbochargers adopting ceramic turbine rotors (CTR) have been successfully introduced for the purpose of improving vehicle acceleration response, the first ceramic turbocharger rotor made up of silicon nitride (material code: SN-60) was developed by NGK insulators Limited in 1986. The second generation turbocharger rotor for use at high temperatures was equally developed by NGK insulators limited, they adopt a silicon nitride (material code: SN-84EC) possessing high mechanical strength at a temperature up to 1200°C and developed new method of joining the ceramic rotor with its metal shaft. The examples of the turbocharger rotor assemblies made from silicon nitride are shown in figure 8 while figure 9 shows a stand-alone ceramic turbine rotor. The important characteristics of CTR made from SN-84EC is its impact resistance against foreign object damage (FOD) such as oxide particles from the interior of the exhaust manifold [37].

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Fig. 7 - Cross-sectional area ratio as a function of azimuth angle for free vortex assumption [36]

Eq. 1

\[
\frac{R_1}{R_2} = \frac{M_2 \sin \alpha_2}{S M_1 \sin \alpha_1} \left[ 1 + \frac{(\gamma - 1)/2 M_1^2}{1 + [(\gamma - 1)/2 M_2^2]} \right]^{\frac{1}{2}}. \tag{1}
\]

Eq. 2

\[
\frac{A_1}{A_2} = \frac{M_2 \cos \alpha_2}{M_1 \sin \alpha_1} \left[ 1 + \frac{(\gamma - 1)/2 M_1^2}{1 + [(\gamma - 1)/2 M_2^2]} \right]^{-\frac{(\gamma + 1)}/[2(\gamma - 1)]} \frac{P_{02}}{P_{01}}. \tag{2}
\]

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Fig. 8 - Ceramic turbocharger rotor assemblies made from silicon nitride. (Picture courtesy of NGK/NTK Spark Plug Co) [37].

Fig. 9 - Ceramic radial flow turbine from automobile turbocharger (Courtesy Kyocera International Inc.) [38].
Ceramic rolling element bearings

Studies on ceramic rolling element bearings have contributed immensely in the design solutions of high speed turbines, precision machine tools and various automotive engine components due to their capability of withstanding severe conditions of temperature, dynamic load and speed as well as their advantages in lubrication restrictions [39]. They have practical advantages over its steel counterpart mainly due to their inherent mechanical and physical properties [40, 41]. Tables 2 and 3 indicated the potential benefits of ceramics in bearings and the comparison of material properties between ceramic and steel respectively.

<table>
<thead>
<tr>
<th>Demonstrated Performance Improvements</th>
<th>Enhanced System Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Increased Life</td>
<td>- Reduced Specific Fuel Consumption (SFC)</td>
</tr>
<tr>
<td>- Increased Speed</td>
<td>- Increased Time Between Overhaul</td>
</tr>
<tr>
<td>- Reduced Heat Generation</td>
<td>- Increased Power Density</td>
</tr>
<tr>
<td>- Lubrication Starvation Tolerance</td>
<td></td>
</tr>
<tr>
<td>- Increased Operating Temperature</td>
<td></td>
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<tr>
<td>- Increased Corrosion Resistance</td>
<td></td>
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<tr>
<td>- Brinelling Resistance</td>
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</tbody>
</table>

It had been shown in literature that the performance of all-silicon nitride bearings and hybrid ceramic/steel bearings is superior in respect of speed and life when compared with the steel bearings [43-45]. On the other hand, Katz and Hannoosh [42] identified that the full implementation of the concept of the adiabatic turbo-compound diesel engine (ATDE) requires bearings which do not require lubrication or oil cooling thereby making the dry lubricated ceramic bearings a favourable choice. The recent investigations by Shoda et al. [46] revealed that silicon nitride (Si₃N₄) materials with sufficient life and reliability were developed as rolling element bearings couple with the fact that hybrid ceramic ball bearings made from silicon nitride and with steel rings have been in the market and are used in machine tool spindles under high speed operations for the past decade. Already there had been an intensive research in the last two decades on how to apply hybrid bearings under severe conditions, for example, in automotive and gas turbines engines [47-49]. Bearing elements having ball bearings made from silicon nitride or combination of zirconia and silicon nitride ceramics have been successfully developed as can be seen in figure 10.

![Example of different ceramic rolling element bearings](https://example.com/fig10.jpg)

**Fig. 10** - Examples of different ceramic rolling element bearings [50].
Summary

Although there may be other existing works on the use of ceramics for automotive application, it can be clearly seen that what has been reported in this review were ceramic applications in the major automotive engine components for whose optimization have tremendous influence on the improvement of the engine thermal efficiency and output power. The advantages of ceramics inherent properties such as their resistances to both oxidation, hot corrosion and wear as well as their high thermal insulation has no doubt gave it an offer hand over metals and their alloys as high temperature material candidates for automotive application and it is believed that in the near future ceramics will totally replace metals and their alloys as high temperature material candidates in the field of engineering and technology.

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