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Synthesis of new aluminum nano hybrid composite liner for energy saving in diesel engines

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ABSTRACT

This work aims to replace the conventional cast iron cylinder liner (CL) in diesel engine by introducing lightweight aluminum (Al) 6061 nano hybrid composite cylinder liner (NL) by analyzing the performance, combustion, and emission characteristics of an engine. NL was fabricated by bottom pouring stir casting technique with nano- and micro-reinforcement materials. Experimental results proved that the use of NL increased brake thermal efficiency, in-cylinder pressure, heat release rate, and reduced carbon monoxide, hydrocarbon, and smoke emission in comparison with CL. However, oxides of nitrogen slightly increased with the use of the new liner. No differences in wear or other issues were noted during the engine teardown after 1 year of operation and 2000 h of running. Thus, NL has been recommended to replace the CL to save the energy and to reap environmental benefits.

1. Introduction

Automotive manufacturers are increasingly interested in producing lightweight vehicles with environmental advantages in terms of fuel consumption and emission reductions [1,2]. Replacement of cast iron with Al in the production of the cylinder block is the contemporary method of reducing the engine weight. Failures of internal combustion (IC) engines through cylinder liner and/or piston anomalies are very destructive and affect the engine. If a failure occurs, usually, liner, piston, connecting rod and, at times, engine head are seriously damaged [3].

Excellent thermal conductivity and lower density make Al–Si alloys [4] as a suitable alternative to cast iron in the fabrication of engine components. Aluminum can be regarded as a prospective energy carrier and has a good potential for large-scale integration in global energy storage [5]. A metal matrix composite (MMC) is made up of at least two distinct phases, properly distributed to realize unique combinations of properties that are not attainable by the individual components. It is composed of a matrix and reinforcements (e.g., fibers or particulate phase), in which the reinforcements are surrounded by the matrix [6]. Al-based composites are being increasingly used in automotive, aerospace, marine, and mineral-processing industries owing to their improved specific strength, good wear resistance, higher thermal conductivity, and lower coefficient of thermal expansion, particularly for lightweight cylinder liners [7]. The piston and cylinder is a very important part in an IC engine to convert the heat energy into mechanical one. The advantages derived from MMC liners in comparison with those from cast iron liners are less weight [8], reduced fuel consumption, lower wear rate, longer component life, and lower lubricant consumption. New materials, coatings, and high-tech machining processes that were previously considered to be too expensive and therefore only used in complex applications are now becoming more affordable. Presently, owing to the advancements in processing of materials, development of new materials to suit different applications has become possible. Production of new materials for diesel engine application with extremely high thermal resistance is important so that heat losses are reduced and recovered to be partially transformed into useful work. These engines are commonly known as low heat rejection (LHR) engines and are used to store thermal energy [9–11].

Ceramic whiskers or particulates are commonly used as reinforcement in Al-based alloys because of their high modulus, high hardness, low cost, easy availability, and limited reactivity with Al. The hybrid composites containing graphite (Gr) show superior wear-resistance properties than mono reinforcement [12–14]. Multiple reinforcements (hybrid MMCs) were adopted as they impart improved mechanical, thermal and tribological properties, and they are better substitutes for composites with single reinforcement.

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Nomenclature

Al	aluminum	LHR	low heat rejection
BTE	brake thermal efficiency	MMC	metal matrix composite
BP	brake power	Mn	manganese
CL	conventional cast iron cylinder liner	NL	nano hybrid composite cylinder liner
CO	carbon monoxide	NO_x	oxides of nitrogen
Cu	copper	ppm	parts per million
Cr	chromium	RoHM	rule of hybrid mixtures
CNC	computer numerical control	SiC	silicon carbide
deg.	degree	Si	silicon
Fe	ferrous	SEM	scanning electron microscope
Gr	graphite	Ti	titanium
HC	hydrocarbon	Zn	zinc
HSU	Hartridge smoke unit	ZrO_2	zirconium dioxide
IC	internal combustion		

Increase in friction is detrimental to engine fuel consumption, with piston–liner friction typically accounting for 30% of the total engine friction. Therefore, the addition of lightweight Al matrix material, lower friction solid lubricant, and high-strength ceramic particles has to be considered for hybrid composite cylinder liner-manufacturing application. The combined weight savings alone could result in significant fuel savings over the life of the vehicle [15,16].

From a design viewpoint, one might expect that increase in material hardness should improve the wear resistance of ceramic particle-reinforced Al alloys and hence it will be suitable for cylinder liner application [17–19]. Nanoscale hybrid or composite materials in the form of powders, spheres, fibers, tubes, and coatings have attracted a great deal of interest in diverse fields because of their unique properties that cannot be attained in micro-scale materials [20–22].

The review of literature indicates that use of new developing materials such as MMCs, hybrid MMCs, nano hybrid MMCs, nano- and micro hybrid MMCs for engine cylinder liner application has attracted a considerable research interest in ensuring cleaner environment. However, significant research efforts have been made to study the behavior of nano hybrid composite cylinder liner (NL)-operated IC engine.

In view of the earlier mentioned facts, it is felt that there is a need to study the performance, combustion, and emission characteristics of diesel engine when operated with newly developed lightweight NL in comparison with conventional cast iron cylinder liner (CL). The novelty of the present work pertains to the development of a new NL with both nano- and micro-sized ceramic reinforcements along with micro Gr inclusion to act as solid lubricant with Al matrix material. In addition to the synthesis of NL, an appropriate application of single-cylinder diesel engine has been identified and experimental investigations have been carried out to prove the suitability of the developed NL for selected application with improved performance and environmental benefits. The major advantage of the developed lightweight liner is that it can be adopted in an existing engine cylinder without any modification in the engine structure.

2. Materials and methods

2.1. Materials

2.1.1. Matrix materials

Among Al alloys, Al 6061 is quite a popular choice as matrix material for MMCs because of its better formability characteristics and the possibility of modifying the strength of the composite [23]. Al 6061 was selected as the matrix material for this study based on a multicriteria decision-making tool (the analytical hierarchy process) by comparing six alternative materials, *viz*., Al 6262, Al 7075, Al 6060, Al 6082, Al 6005, and Al 6061. Various criteria were considered for these materials, some of the most important being Brinell hardness number, yield strength, percentage of elongation, fatigue strength, coefficient of thermal expansion, and cost. The melting point of Al 6061 was 650 °C and its chemical composition is shown in Table 1.

2.1.2. Reinforcement materials

Zirconia or zirconium dioxide (ZrO_2) is also one of the most important ceramic materials because of its excellent mechanical, thermal properties, and melting point of 2200 °C that are similar to metals, which makes it suitable for its use in ceramic engines. At the same time, because of higher doping percentages (more than 2.5%), agglomeration of ZrO_2 is more common problem in the Al matrix production [24,25].

Application of Gr as one of the reinforcing components permits creating a film separating the wearing couple without any additional lubricant [26–29]. Melting point of the Gr was 3500 °C, also it is used to make components such as engine bearing, piston, piston rings and cylinder liners. It has good tensile, wear resistance, and thermal conductivity properties [30,31]. The commonly used ceramic reinforcement of silicon carbide (SiC) also has fine mechanical strength, melting point of 1650 °C, and thermal properties with lower density than ZrO_2. To minimize cost and time to prepare nano-scale ZrO_2 particles, equal quantity of micro-SiC was selected to make hybrid NL. In this study, the developed hybrid ceramic reinforcements of nano-ZrO_2, micro-SiC, and solid lubricant particles of micro-Gr were combined to make NL.

ZrO_2 particles were prepared by using a high-energy ball-mill with a frequent cooling time of every 2 min to avoid the formation of agglomeration. The average particle size was determined to be 98.29 nm using Particle Size Analyzer (NANOPHOX (0143 P) Sympatec GmbH, Clausthal-Zellerfeld, in Germany operated with the Windox 5 software package. The composition of NL is summarized in Table 2.

2.2. Synthesis of NL

2.2.1. Prediction of mechanical and thermal properties through rule of hybrid mixtures

The physical and mechanical properties of the developed hybrid composite were evaluated through rule of hybrid mixtures (RoHM) approach [32,33]. The standard property values of matrix and