A PRELIMINARY STUDY ON THE DESIGN AND FABRICATION OF CAR GEAR ROTOR (DISC) BY USING Al_2TiO_5 FUNCTIONAL GRADED MATERIALS

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Abstract— Composite materials are popular substitute materials for automotive, sports, industry, medical, aerospace and vast engineering fields. Aluminium titanate (AT) (Al_2TiO_5) is a promising engineering material because of its low thermal expansion coefficient, excellent thermal shock resistance, good refractoriness and non-wetting with most metals. Aluminium titanate, (Al_2TiO_5) with the pseudo-brookite structure is so far the only compound in the alumina-titania system. It is an excellent refractory and thermal shock resistant material due to its relatively low thermal expansion coefficient ($1\times10^{-6\circ}C^{-1}$) and high melting point (1860ºC). AT is only thermodynamically stable above 1280°C and undergoes a eutectoid-like decomposition to α-Al_2O_3 and TiO_2 (rutile) in the temperature range of 900-1280°C.

In this paper an innovative conceptual design approach to compare between developments of aluminium alloy based on metal matrix composites (MMCs) and the alumina-aluminium titanate (AAT) Functional Graded Materials (FGMs) in the automotive rotor/disc brake system is presented. This includes the methodology of conceptual stage, the evaluation systems and the computer aided design (CAD) for illustrating and choosing the ultimate design concept.

Keywords: *Metal Matrix Composites (MMC), Functional Graded Materials (FGM)*

I. INTRODUCTION

Most recently, ceramic materials have played an important role in the electrical industry because of their high electrical resistivity, and have come to be associated with a wide variety of other engineering applications. Most of these utilize their outstanding physical properties, including their ability to withstand high temperatures (refractoriness and refractory coatings), provide a variety of electrical and magnetic properties (solid-state electronics), and resist wear (coated cutting tools) [1]. In general, ceramics are hard, brittle, high melting point materials with low electrical and thermal conductivity, low thermal expansion, good chemical and thermal stability, good creep resistance, high elastic modulus and high compressive strength.

In comparison to conventional composite materials, advanced ceramics designs are established by using the structure of crystallography, composition of elements, preparation synthesis, sintering temperature, microstructure on damage-tolerance and heating environment atmosphere. Furthermore, the properties of ceramics are maintained by the properties of each phase present in the sample. There are several factors that determine the phase composition and how they operate in ceramic systems.

Especially, in terms of mechanical properties, strengthening and toughening, hardness, less weight and low thermal expansion, the chemical processes involved in the interfacial reactions and fabrication of metal matrix composite (MMCs) and functional graded materials (FGMs) are more complex and challenging. In this paper, the comparison usage of functional graded materials (FGMs) Alumina-AT and metal matrix Composite (MMCs) Alumina-AT will be presented.

II. BACKGROUND

A. *Funtionally graded materials (FGMs)*

Functionally graded ceramics (FGMs) is the next evolution of layered structures. It consists of graded compositions that are dispersed across the ceramic. This graded method produces a gradual improvement of properties across the ceramic at a steady pace, dependent upon the method of the creation of the layers. Functionally graded materials seek to produce strong interlayer bonding and to eliminate residual macroscopic stresses. Functionally graded materials created by the infiltration method and thermal decomposition method show a continuous change across the sample. These methods have been mostly pioneered by Low and co-workers [2] and provided admirable results in contact damage resistance due to micro damage caused by the build up of residual stress to contain the crack propagation whilst retaining strength and wear resistance at the grades closer to the outermost layer. However, due to their very thin graded interface, a path to the soft core can still be breached by a heavy load. Another process, which is the one utilized in this project, is the creation of thin interfaces of graded composition sandwiched between two differing layers. The outermost layers will provide strength and wear resistance whilst the inner layer will provide toughness. It is speculated that the graded interfaces will provide contact damage resistance with retention of strength and wear resistance. However these values will vary depending upon the composition and thickness of the graded interfaces.

FGMs can be designed at the microstructural level to tailor a material for the specific functional and performance requirement of a purpose application. FGMs may be investigated in various ways to produce several type of continuous component change. Therefore, by functionally-grading Al_2O_3/AT composites using thin interfaces of graded Al_2O_3/AT composition layers between the Al_2O_3/AT bilayers, the best qualities of both ceramics can be imparted whilst attempting to minimize unwanted traits such as the lack of damage tolerance in the alumina and the low strength of the AT.

In functional graded materials (FGMs), the properties change gradually. Also known as alumina, Al_2O_3 is the only solid oxide of aluminium, it has a hexagonal close packed (HCP) lattice crystal structure. Alumina itself has since found an enormous range of technological and industrial applications due to its properties such as high thermal conductivity, wear resistance, high hardness, resistance to many corrosive media, abrasion resistance, low density, and high electrical resistivity. It is only limited by low toughness and low tensile strength. However, due to its high demand in applications, alumina is frequently incorporated with other materials to obtain more advanced specific properties and microstructures.

For this reason, the mechanical performance of ceramics is very sensitive and it is important to play its role in building the new phase composition and morphology of advanced ceramics, such as Functional Graded Materials (FGMs) microstructures.

Due to several interesting properties, meanwhile, ceramics manufactured from aluminum titanate (AT) exhibit extremely good resistance to thermal shock. This is due largely to the very low thermal expansion coefficient attributed to significant anisotropy in the material's properties. Aluminum titanate (AT) is widely used as a refractory material and as a thermal insulator in engine components by virtue of its low thermal expansion coefficient (1×10^{-6} $^{\circ}C^{-1}$), high melting point (1860ºC), low thermal conductivity, and excellent thermal shock resistance.

The full potential of AT has been limited by its low fracture toughness, low mechanical strength and poor high–temperature stability below 1280ºC. By adjusting the composition through addition of stabilizers such as SiO_2, Fe_2O_3 and MgO, the thermal and mechanical performance of AT can be greatly enhanced. Low and co-workers [2] have shown that the surface decomposition of AT at 1100°C is significantly enhanced in vacuum (10^{-4} torr): more than 95% of AT decomposed after 5 hours' soaking compared to less than 30% in atmospheric air. This suggests that the process and the temperature range of decomposition of AT are dependent on the oxygen partial pressure. It was further found that the decomposition process of AT in vacuum was surface-initiated in contrast to the bulk-initiation process in air. This unique surface-initiated decomposition has offered the potential for the microstructure design of functionally-graded AT composites in a vacuum furnace [2].

B. Metal matrix composite (MMCs)

The ever increasing demand for light weight, fuel efficiency and comfort in automobile industries has lead to the development of advanced materials along with optimum design. MMCs are widely used in industries, as they have excellent mechanical properties and wear resistance. Particulate-reinforced composites cost less than fibre-reinforced composites due to the easy manufacturing process. In addition to improved physical and mechanical properties, particulate-reinforced composites are generally isotropic and they can be processed through conventional methods used for metals. Silicon Carbide-reinforced aluminium composites are widely used as substitute materials for cylinder heads, liners, pistons, brake rotors and calibers in automotive industry [9].

III MECHANICAL CHARACTERISATION OF GRADED PROPERTIES ALUMINA/AT

After contact damage via Vickers indentation testing, it was found that the graded layers provide the necessary damage resistance to control subsurface cracking at loads of 5 kg, 10 kg and 20 kg by the 75% Al_2O_3/ 25% Al_2TiO_5. Standard Vickers hardness testing across the cross section of various samples showed that hardness decreased across the cross section, starting high at the outer Al_2O_3 layer and whittling down to lower levels at the inner AT layer. This is inversely proportional to the increase in the fracture toughness of the sample which was increasing from the Al_2O_3 layer to the AT layer. Crack energy was generally absorbed by the first graded layer of 25% AT, 75% Al_2O_3. This is due to the micro damage that occurs caused by the AT presence. The addition of graded layers aided in the reduction of these residual stresses compared to the non-layered samples, however additional layers would further aid in the reduction of residual stresses without compromising the toughness, possibly making the samples viable for more rigorous testing methods such as environmental effects on growth of fatigue cracks. The new determination process of decomposition in Al_2TiO_5 is reversible and that self-recovery method of decomposition Al_2TiO_5 is developed [3].

IV FURTHER DESIGN AND FABRICATION WORK

Achievement of reduced fuel consumption as well as reduced green house gas emission in automobiles is a current issue of utmost importance. Use of light-weight materials in auto components can contribute significantly towards achieving this goal. At present, cast iron brake rotor/disc is heavy, so it reduces the car's fuel efficiency. Auto brake system particularly the drum/disc rotor traditionally made from cast iron is an attractive candidate for material substitution [4–11].

Efforts have therefore been directed in recent years towards the development of suitable light-weight materials for brake rotor. Aluminum alloy based metal matrix composites (MMCs) with ceramic particulate reinforcement have shown great promise for such applications [5]. These materials having a lower density and higher thermal conductivity as compared to the conventionally used grey cast irons are expected to produce weight reduction of up to 50-60% in brake systems. Moreover, these advanced materials have the potential to perform better under such severe service conditions as higher speed, higher load etc. which are increasingly being encountered in modern automobiles.

Since brake is a crucial component from safety point of view, materials used for brake systems should have very stable and reliable thermal abrasive wear and frictional heat properties under varying conditions of velocity, temperature, and environment. These materials therefore require extensive investigation and quality control during development and production stages.

Although numerous studies have been devoted to the tribological properties of Al-MMC [6-8] much is yet to be understood about the thermal abrasive wear and frictional heat of this complex material in different conceptual design. Therefore the aim of this project is to simulate aluminum metal matrix composite auto brake rotor and investigate systematically the thermal abrasive wear and frictional properties and to fabricate actual Al-MMC brake rotor with optimum conceptual design.

A. *Design considerations*

Surface Rejuvenate Features:

These features are to refresh the contact surface between the brake pad and the rotor from unwanted lubricants such as brake pad and disc/rotor wear particles, external environmental dust such as sand, water and even trapped air pockets. This unnecessary lubrication causes the contact area between the pad and the rotor to slip; hence reducing the vital friction element of the brake. Six concepts of surface rejuvenate features are explained as below:

Concept 1: Numerous repeated circular grooves provide an ultra high refresh rate while causing the brake pad to suffer from immense wear rate. This concept applies to extreme users with high brake pressure applications where they push their car to the limit on harsh environment. The high refresh rate sorts out debris at a high rate giving maximum friction for the pad and disc/rotor contact areas.

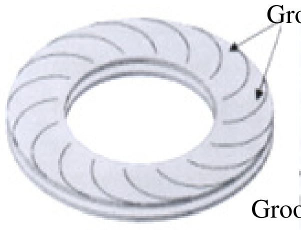

Figure1a. Concept 1

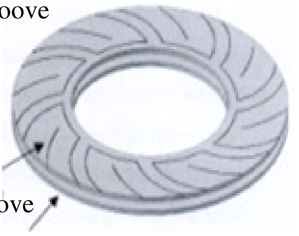

Figure 1b. Concept 2

Concept 2: This concept offers the second highest refresh rate among the others. It has various multiple grooves aligned uniformly to satisfy demanding drivers.

Concept 3: the 'V' shaped grooves restore the surface quickly and uniformly without sacrificing much contact areas. Short multiple grooves 'V' joined together offer a well balanced performance.

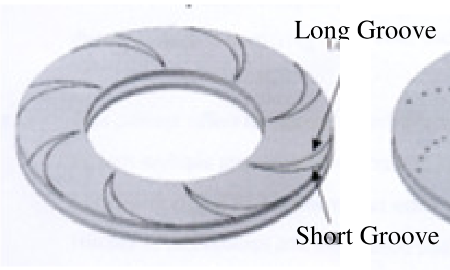

Figure1c. Concept 3

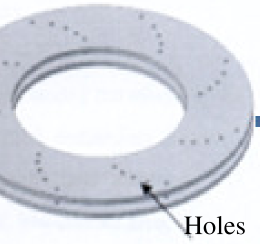

Figure 1d.Concept 4

Concept 4: Holes are basically driven across the top surface to the bottom surface of the disc/rotor. These holes are to remove fragments and layers of fluid from the surface. The weaknesses of this concept; holes only refreshes a certain part of the contact surface, stress concentration occurs and causes cracks.

Concept 5: The double grooves featured in this concept offers high refreshing rate with a moderate contact area. The high refreshing rate indirectly generates high shear stress by the grooves to the pads causing intense pad wear rate.

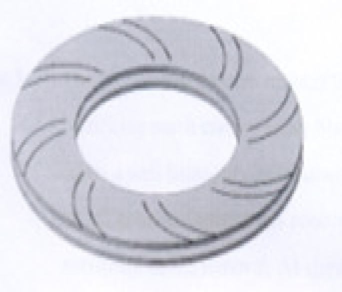

Figure1e. Concept 5

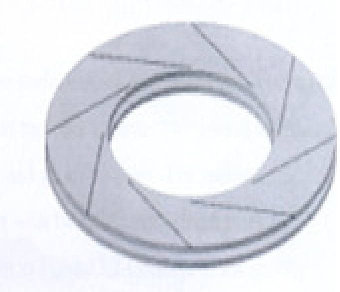

Figure 1f. Concept 6

Concept 6: This concept consists of straight grooves carved on surfaces of the disc/rotor. Straight grooves are easily carved with a low cost and with minimal errors. Straight grooves gradually refresh the surface giving a maximum friction and contact area between the pad and the disc without sacrificing much pad wear.

Ventilation cooling fins:

The brake systems convert the vehicle's kinetic energy into thermal energy. Heat is then dissipated into the air by internal cooling fins of disc/rotor. The rate of heat transfer affects the coefficient of friction between the brake disc and pad, the life span of disc, wear rate and heat deformation. Six conceptual ventilation cooling features are shown in Figure 2a-2f. Each conception has its unique features and geometry.

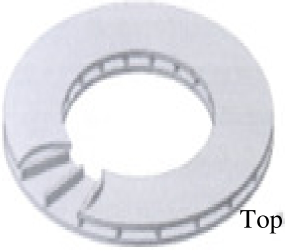

Figure 2a. Concept 1

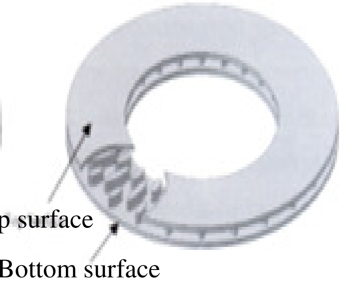

Figure 2b.Concept 2

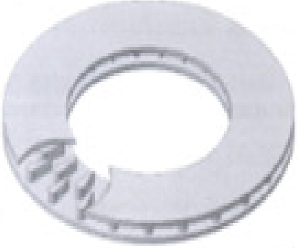

Figure 2c. Concept 3

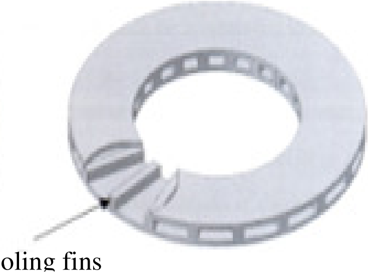

Figure 2d.Concept 4

Figure2e. Concept 5

Figure 2f. Concept 6

Six conceptual ventilation cooling features are shown in Figures 2a-2f. Each conception has its unique features and geometry. The best concept should be selected based on the following criteria: 1. Contact area with air, 2. Manufacturability, 3. Heat dissipation, 4. Cost effectiveness etc.

Illustration of Assembly Concept:

The brake disc rotor could either be assembled using the single piece or double piece concept, (Figures 3(a) and 3(b)), both having advantages and drawbacks, depending upon the users' applications. Several useful criteria for choice of assembly design are such as heat transfer ability, fabrication process and maintenance.

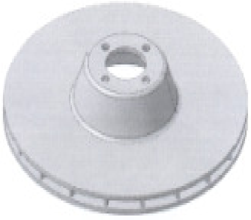

Figure 3(a)
Single piece disc/rotor

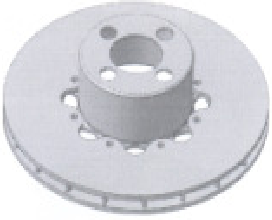

Figure 3(b)
Double piece disc/rotor

Material approach:

Three alternative material approaches are to be investigated in the proposed research. The concepts are as follows:

1. Sandwiched functional graded material approach

Figure 3 represents the sandwiched functional graded material approach The primary focus of sample preparation will be the creation of thin interface of graded 50% Al_2O_3/ 50% Al_2TiO_5 composite layers sandwiched between two outer layers of fully pure Al_2O_3.

Al_2O_3 (100%)
Al_2O_3 (50%) + Al_2TiO_5 (50%)
Al_2O_3 (100%)

Figure 3. Functional Graded 50%Al_2O_3 / 50% Al_2TiO_5 design

2. Molar ratio multi-layered functional graded material approach

Initially, Functionally-graded AT will be synthesized from high purity Al_2O_3 and TiO_2 mixed in the proper ratio by weight with MgO added as both sintering aid and stabilizer. Graded layers will include four batches of powder comprising of a 100% Al_2O_3, the second, third batches are 75% Al_2O_3/25%AT, 25%Al_2O_3/75% AT respectively, and fourth batch will be pure outermost 100% Al_2O_3 layer (Fig 4). Pure Al_2O_3 will be used as standard. Second, third batches are called Functional Graded samples, initially pressed at 150 MPa, followed by hot-isostatic pressing at 200 MPa to ensure more uniformity in powder compaction.

Al_2O_3 (100%)
Al_2O_3 (75%) + Al_2TiO_5 (25%)
Al_2O_3 (25%) + Al_2TiO_5 (75%)
Al_2O_3 (100%)

Fi

Al_2O_3 (75%) + Al_2TiO_5 (25%)

3.

Th stir casting technique using Al_2O_3 alloy and 25% Al_2TiO_5 particles and machined to the required size.

V Conclusions:

Expected research outcomes

1. The MMC and FGM brake discs are expected to perform differently.

2. The disc performance shall show different characteristics under varied thermal loading conditions.

3. The MMC and FGM brake discs are expected to be lighter and hence helpful to increase the vehicle's fuel economy. The MMC and FGM brake discs are expected to have a longer life span.

4. The design features of the FGM and MMC brake discs are expected to be more advanced and appropriate in terms of surface rejuvenating, ventilation cooling fins, single or double pieces, and other related features.

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