On the Problem of Novel Composite Materials Development for Car Brake Rotor

P. R. K. Fu, A. Gorin, D. Sujan, Z. Oo

***Abstract*—**This paper presents a study of the potential materials that are suitable for the development of the automotive brake disc. Two new materials are proposed as an alternative material to the conventionally used gray cast iron for the disc brake, which are namely Metal Matrix Composite (MMC) and Functionally Graded Material (FGM). MMCs with ceramic particulate reinforcement are found to have a low density and high thermal conductivity compared to the cast irons. Two particulate reinforcements, Al_2O_3 and SiC were being considered for MMC. On the other hand, FGM has demonstrated high thermal shock resistance, better wear resistance and low density. Preliminary investigation indicated that MMC acquired improved hardness property. Meanwhile, the hardness property of FGM with Al_2O_3 and Al_2TiO_5 as layered composites materials can be further improved.

***Keywords*—**Automotive disc brake, functionally graded material, metal matrix composite

I. Introduction

An automotive brake disc is a device that slows or stops the motion of a wheel while it runs at a certain speed. The construction of an adequate brake disc that satisfies the increasing demand for low maintenance car has been a popular research in the automotive manufacturing area.

In general, an automobile brake system consists of a brake disc and brake pads in order to maintain a steady friction coefficient. Braking system is a vital safety component of the ground-based transportation systems. Thus the structural materials used in developing the brakes have to fulfil a series of functions. They ought to be dependable, durable, corrosion resistant, structurally sound, and economically viable [1]. Most disc brake rotors in use today are made from gray cast iron, typically containing 2% to 4.5% dissolved carbon within its matrix and various additives as well [2]. Due to its low cost, relatively ease of manufacture and thermal stability, cast iron is a more specialized material for brake applications particularly for almost all the automotive brake dics. Gray cast iron possesses low thermal conductivity (47.3W/m°C) and low specific heat capacity (0.498J/g.K) [3]. The hydraulic pressure exerted during typical braking procedures, lies between 2MPa and 4 MPa. Friction makes rotor reach (within a very small periods of time), temperatures as high as 800°C, resulting in a thermal gradient between the surface and the core of the rotors, which may reach up to 500°C.

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This will most likely lead to warping of the disc brake.Therefore, higher thermal conductivity and higher specific heat capacity are most preferred to promote efficient thermal energy dissipation and hence avoid the overheating of the disc brake. Subsequently, this leads to the development of advanced materials for the disc brake.

The main contribution of this paper is two-fold. First, we fabricate the two proposed materials. Second, we perform a study on these materials, specifically their hardness property and their characteristic results are analyzed towards the end of this paper.

The rest of this paper is organized as follows. The detailed description of MMC and FGM are reported in Section II and III respectively. Section IV listed the procedures required in our experimental work on the fabrication of MMC and FGM materials and the hardness test. The results derived from our experiments are analyzed and discussed in Section V. Concluding remarks are drawn in Section VI.

II. Metal Matrix Composite

A composite material is a material consisting of two or more physically and/or chemically distinct phases. The reinforcing component is distributed in the continuous or matrix component. When the matrix is a metal, the composite is termed as Metal Matrix Composite (MMC) [4]. MMCs are popular substitute materials for automotive, satellite systems, ballistic protection, general industries, sporting goods, aviation and are also vastly applied in other engineering fields. This is because MMC possesses excellent mechanical properties and wear resistance. Research showed that the wear resistance of the MMC can be attributed to the strength and hardness of the SiC particles [3]. If the SiC particles remain well bonded to the matrix during the sliding wear process, the aluminium matrix surrounding them will be worn away and all contacts will be between the friction material and SiC particles in the composite. Therefore, the wear resistance of the composites is related to the hardness property of the SiC particles. In addition, Zhang and Wang [5] found that the friction performances and wear resistance for brake material sliding against drum brake with large-size SiC particles are better than those against the drum brakes with small-size SiC particles. Other than that, Tatar and Ozdemir [6] found that the thermal conductivity of the Al_2O_3 particulate reinforced aluminium composites (Al/Al_2O_3-MMC) decreased with the increasing of Al_2O_3 volume fraction. They found that Al-MMC 45 vol% Al_2O_3 showed a lower thermal conductivity as compared to Al-MMC 15 vol% Al_2O_3. Hence in this paper, the hardness property is investigated by varying the weight fraction (from 5% to 15%) of the reinforcement particles (SiC and Al_2O_3) in the MMC. Other than that, large-size SiC particles will be used as well.

III. Functionally Graded Material

Functionally graded materials (FGM) are defined as those materials in which the volume fraction of two or more constituents is varied smoothly and continuously as a function of position along certain dimension(s) of the structure [7]. Functionally Graded Materials (FGM) has demonstrated to be advantageous beyond mechanical applications extending to electronic, optical, nuclear, biomedical, and other fields.

Low et al [8] found that layered graded materials (LGM) formed by a homogeneous Al_2O_3 layer and a graded heterogeneous Al_2TiO_5/Al_2O_3 layer exhibited a relatively 'soft' surface that encased a hard core. The presence of the 'soft' surface regions is due to the high concentration of Al_2TiO_5, which displays a low hardness value. Bueno et al [9] suggested that further studies be conducted to establish the effect of different stacking orders and layer thickness on the mechanical behaviour of the laminates. The method they have used in manufacturing the layered composites was slip casting. They discovered that laminated layer Al_2O_3-Al_2TiO_5 composite's thermal conductivity similar to that of alumina (35.6W/m°C) [10]. The laminated layer Al_2O_3-Al_2TiO_5 composite showed low wear rates.

In this paper, the hardness property of FGM formed by sandwiching thin interface of graded Al_2O_3/Al_2TiO_5 composite layers between an outer layer of Al_2O_3 and an inner layer of Al_2TiO_5 is studied.

IV. Experimental Procedure

The materials used for fabricating MMC are aluminium alloy A356 as a matrix material and silicon carbide, SiC (105µm) as reinforcement particles. MMC is being fabricated by melting the metal in a furnace then reinforcement particles are being added in and stirred slowly. As for FGM, commercial rutile (TiO_2) and alumina (Al_2O_3) were used as materials. Uniaxial press is used to sandwich the graded layers together.

A. Metal Matrix Composite

Aluminium alloy A356 rods were first cut into smaller pieces with each 1cm thickness. 500g of 1cm thickness with each piece of aluminium alloy and 3 wt% of magnesium (wetting agent) were melted in the furnace at temperature of 700°C. Preheated reinforcement particles of silicon carbide were then added into the molten aluminium alloy. The reinforced particles were preheated beforehand at 900°C in the furnace to remove all the moisture on the particles' surface for better binding results. The compositions of composite materials that were being fabricated were: Al with 0% SiC, Al with 5% SiC, Al with 10% SiC, Al with 15% SiC all with different weight percentage. Silicon carbide was added into the molten metal matrix using the vortex method. Vortex was created by stirring the molten material manually at a rapid speed. Silicon carbide was then added at the side of the vortex and stirring was done continuously for a few minutes. The vortex method is believed to be able to distribute the particles among the metal matrix more evenly [11]. Stirring was done for 4 intervals, every 30 minutes for a duration time of 2 to 3 minutes. Stirring must not be done vigorously to avoid air bubbles and impurities on the surface because that could lead to porosity. In order to achieve proper dispersion of particles among the matrix metal, the temperature was reduced to 550°C. This was done to allow the liquid mixture to turn into a semi solid state so that when force was applied onto the particles, there would be abrasive collision between both particles and matrix metal. After the final stirring, the molten metal composite was left to cool in the furnace overnight to avoid rapid cooling. The final casted Al-MMC product was then machined into specific specimen sizes. The above experimental procedures were repeated with Al_2O_3 as the reinforcement particles.

B. Functionally Graded Material

Aluminium titanate powder was created by properly synthesizing the rutile and alumina ($Al_2O_3 + TiO_2 \rightarrow Al_2TiO_5$) provided and milled using a Rocklab ring mill. The primary focus of sample preparation was the creation of thin interface of graded Al_2O_3/Al_2TiO_5 composite layers sandwiched between an outer layer of Al_2O_3 and an inner layer of Al2TiO5. Only three graded layers were included in most of the samples comprising of a 75% Al_2O_3 / 25% Al_2TiO_5 grade located next to the Al_2O_3 outermost layer followed by a 50% Al_2O_3 / 50% Al_2TiO_5 grade then a 25% Al_2O_3 / 75% Al_2TiO_5 grade which was located next to the Al_2TiO_5 innermost layer (Figure 1). Layering was done by the use of a 15 mm inner diameter cylindrical steel die. 2 mm thickness of Al_2TiO_5 was placed first into the die before a layer of 25% Al_2O_3 / 75% Al_2TiO_5 was placed on top, followed by 50% Al_2O_3 / 50% Al_2TiO_5, 75% Al_2O_3 / 25% Al_2TiO_5 and finally 1 – 4 mm of Al_2O_3. The graded layers varied in thickness with either all of them being 0.1 mm, 0.3 mm, 0.5 mm or 0.7 mm thick. The samples were then uniaxially pressed at 5000 PSI for 20 seconds by a Blackhawk Uniaxial Press. Three batches of graded materials were produced, all at varied sintering temperatures and methods of pressing. The first batch comprised of non-graded, 0.1 mm graded layers, 0.3 mm graded layers, 0.5 mm graded layers, 0.7 mm graded layers and four 50/50 graded layer (0.1 mm, 0.3 mm, 0.5 mm and 0.7 mm) samples that were sintered at 1500°C for an hour. The second batch comprised of non-graded, 0.1 mm graded layers, 0.3 mm graded layers and 0.5 mm graded layers samples that were cold isostatically pressed and sintered at 1550°C for 1 ½ hours. The final batch was comprised of non-graded, 0.1 mm graded layers, 0.3 mm graded layers and 0.5 mm graded layers samples that were sintered at 1515°C for an hour.

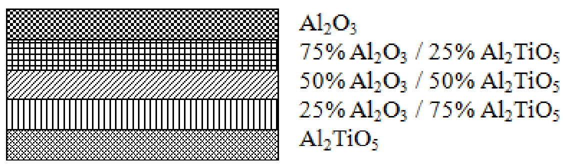

Fig. 1 Graded layers FGM design

C. Hardness Testing Procedure for MMC

Hardness test was being carried out by the Rockwell hardness test apparatus. For this hardness test on the MMC samples, the scale HRB was used. Based on the HRB scale, a load 100kgf is to be applied on the MMC sample through a 1/16 inch diameter spherical shaped steel indenter. The load was applied to the sample for a time of 10 seconds and the hardness values were obtained immediately from the apparatus.

D. Hardness Testing Procedure for FGM

Vickers microhardness testing was utilized to calculate hardness across the cross section of selected samples from the first two batches of the functionally graded materials (FGM) samples prepared. The selected samples consisting of non-graded, 0.1 mm graded, 0.3 mm graded, 0.5 mm graded and 0.7 mm graded samples were mounted in resin and the cross section was polished from 20 µm surface roughness to 1 µm surface roughness. Samples were indented across the cross section of the samples with an average of 6 indents per sample, starting from the alumina layer to the aluminium titanate layer. The resulting indent was then viewed under a microscope and measured for radial crack length and indent diameter in order to calculate hardness (GPa).

V. RESULTS AND DISCUSSION

A. Hardness Results for MMC

From Fig. 2 and Fig. 3, it can be observed that the hardness property for MMC increased with the increased of particle reinforcements (Al_2O_3 and SiC).

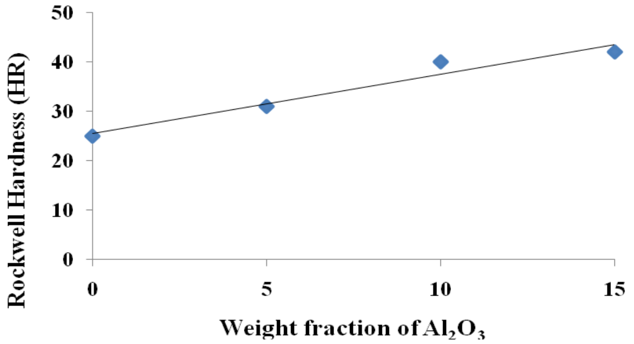

Fig. 2 The variation of the hardness values with weight fraction of Al_2O_3 reinforcement particles around room temperature

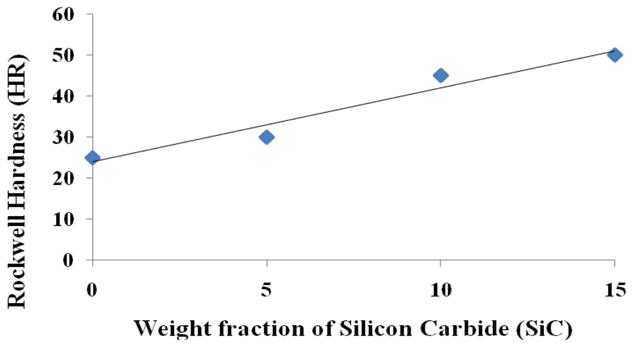

Fig. 3 The variation of the hardness values with weight fraction of SiC reinforcement particles around room temperature

B. Hardness Results for FGM

In Fig. 4, the highest hardness value in the FGM can be seen at the beginning of the alumina layer. The hardness values decreased until it reached very low results of 0.4 GPa by the end of the first graded layer, 75% Al_2O_3 / 25% Al_2TiO_5. Hardness in the homogeneous alumina layer should have been of a higher value as this layer should provide resistance to deformation by surface indenting or abrasion. This could have been done in a number of ways such as using fillers or reinforcements in the alumina matrix. Another method of improving the protective properties of the homogeneous alumina layer would be to increase the thickness of the layer therefore it will take a higher load in order for cracks to propagate towards the first graded layer.

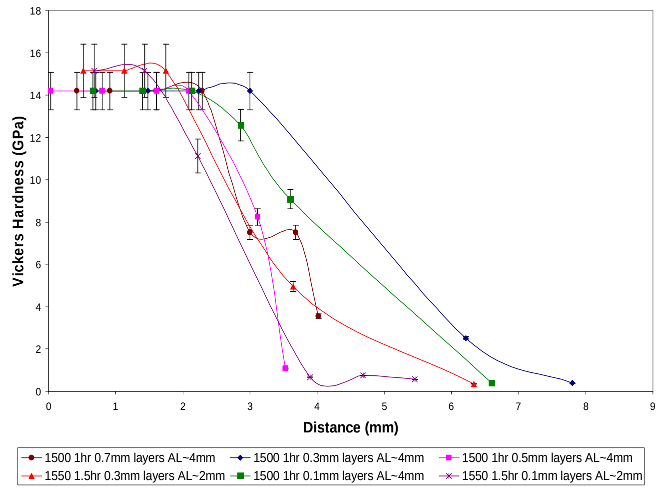

Fig. 4 Hardness results for different thickness of graded layers versus the distance of surface indenting

VI. CONCLUSIONS

A disc brake should acquire a combination of properties such as good thermal capacity, acceptable friction coefficient, good compressive strength, wear resistant and economically viable. From the experiments done, MMC showed improved hardness. However further investigation should be done on the hardness property in relation to the wear rate for MMC. As for FGM the hardness property can be improved by increasing the alumina layer or using reinforcements in the alumina matrix. Further investigation on the mechanical behaviour ought to be performed, specifically for different stacking orders and layer thickness of FGM.

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