Chapter 2
Literature Review

Applications of metal matrix composites in defense, aerospace and light vehicles have been reported by Rittner (2001). She has concluded that the scope for MMC in all the above areas were optimistic and suggested further improvement in processes, selection of alloy, selection of reinforcement and selection of components to reduce the cost of end product. Robert (2001) has presented various forms of aluminium alloys and their applications. Based on his survey on the growth of aluminium alloys, he concluded that 32.2 % of the aluminum was consumed in transport industry in different forms. Foltz and Charles (1991) have presented various matrix alloys, reinforcements and their applications in space, defense, automotive and electronic packaging. They also presented the possible applications of MMCs in making automotive components like pistons, cylinder sleeve, connecting rod and brake discs. Many Researchers (Suresh et al. 1993; Kevorkijan 1999; Rohatgi 1991; Nakanishi et al. 2002) have presented the applications of MMCs for the automotive components and the feasibility of manufacturing these materials. Surappa (2003) has presented an overview of aluminium matrix composite material systems on aspects relating to processing, microstructure, properties and applications. Many challenges of using the metal matrix composites are producing high quality and low cost reinforcements, developing simple economical and portable non-destructive kits to quantify undesirable defects, developing less expensive tools for machining and cutting and also developing re-cycling technology. The following chapters discuss the issues in design and manufacturing of an automobile brake drum.

2.1 Automotive Brake System

The brake system is the most important system in vehicles (Fig. 2.1). It converts the kinetic energy of the moving vehicle into thermal energy while stopping. The basic functions of a brake system are to slow the speed of the vehicle, to maintain

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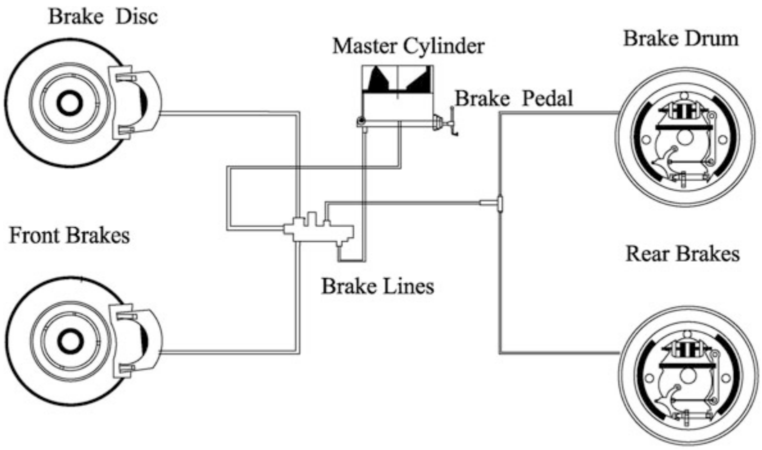

Fig. 2.1 Automotive brake system

its speed during downhill operation, and to hold the vehicle stationary after it has come to a complete stop. The brake system is composed of master cylinder, brake lines, wheel cylinders or slave cylinders, shoes or pads, drum or disc and brake fluid the master cylinder is located under the hood and it is directly connected to the pedal. It converts the foot's mechanical pressure into hydraulic pressure. A mater cylinder has two complete separate cylinders in one housing, each handling two wheels. Even if one cylinder fails, the other cylinder will stop the vehicle. The brake fluid travels from the master cylinder to the wheels through a series of steel tubes. It uses non-corrosive seamless steel tubing with special fittings at all attachment points. Wheel cylinders are cylinders in which the movable pistons convert the hydraulic pressure of the brake fluid into mechanical force. It consists of a cylinder that has two pistons, one on each side. Each piston has a rubber seal and a shaft that connect the piston with a brake shoe. The wheel cylinders of the brake drum are made up of a cylindrical casting, an internal compression spring, two pistons, two rubber cups or seals, and two rubber boots to prevent the entry of dirt and water. The wheel cylinders are fitted with push rods that extent from the outer side of each piston through a rubber boots, where they bear against the brake shoes. Hydraulic pressure forces the pistons in the wheel cylinder which forces the brake shoes or pads against the machined surface of the brake drums or rotors. When the brake pedal is depressed, it moves the pistons within the master cylinder, pressurizing the brake fluid in the brake lines and slave cylinders at each wheel. The fluid pressure causes the wheel cylinders pistons to move, which forces the shoes against the brake drums. Brake drums use return springs to pull the pistons back away from the drum when the pressure is released. The brake shoes consist of a steel shoe with the friction material or lining materials are riveted or bonded to it. The lining materials are either asbestos (organic), semi-metallic, or asbestos free materials. The lining material consists of fibers, fillers, binders and friction modifiers. The brake drums are made up of cast iron and have a machined surface inside the drum where the shoes make contact. The brake drums will show the signs of wear as the lining seats themselves against the machined surface of the brake drum. When new drums are installed, the brake drum should be machined smooth. The brake fluid is special oil that has specific properties. It is designed to withstand cold temperatures without thickening as well as very high temperatures without boiling.

2.2 Materials Used in Automotive Brake Drum

2.2.1 Cast Iron

Cast iron is normally used for making the brake rotors and drums. The excellent heat absorbing capacity, low cost, simple manufacturing methods are the reasons for using the cast iron in these applications. Low corrosion resistance, rusting, brake noise, and high density are the disadvantages of using this material for brake applications. Since the brake rotors/drums represent unsprung rotating weights, increase in their mass will also increase the inertia of the rotating parts and can also decrease vehicle dynamics and acceleration. Gray cast iron with type-A graphite flakes with a pearlitic matrix of low ferrite and carbon content is used.

2.2.2 Compacted Graphite Iron

In recent years, the truck industry was in need of a lightweight brake drum. The result is a new lightweight brake drum with higher strength to be cast is Compacted Graphite Iron (CGI). Specifically because of CGI, they were able to enter a market in which neither had participated before. Designing a brake drum with cast CGI resulted in a wheel component that had high heat transfer, long life, low wear and reduced weight. CGI combines high strength with reduced weight when compared to iron or steel brake drums. It can reduce a casting's weight by 10–25 %. Its higher strength allows for thinner sections because the brake drum can withstand the loads applied. CGI has sufficient heat flow to move the heat from the brake shoe area. Cueva et al. (2003) studied and compared the wear resistance of three different types of gray cast iron (grade 250, high carbon gray iron and titanium alloyed gray iron) used in brake rotors and compared with the results obtained with a compact graphite iron (CGI). Based on the investigations they concluded that the compact graphite iron more wear higher frictional forces and temperatures.

The shape of the graphite flakes found in CGI and the metal's pearlite/ferrite matrix ratio determines its mechanical and physical properties. Figure 2.2 shows the rounded edges of graphite within CGI suppress cracking that would occur with

Fig. 2.2 Microstructure of C. G. iron

Fig. 2.3 A typical CGI brake drum

sharp-flaked edges typically found in gray iron. The CGI brake is shown in Fig. 2.3. These factors increase the tensile strength to 450 MPa relative to gray iron (276 MPa). The modulus of elasticity of CGI varies from 138–165 GPa. The variations result from differences in graphite shape and amount, section size and matrix structure. The elastic modulus of dynamically loaded CGI components may be 50–75 % higher than identically designed gray iron castings. The increased modulus is equals increased stiffness.

2.2.3 Steel Shell Cast Iron Composite Brake Drum

The protective steel shell surrounding the cast iron brake surface affords major weight savings as well as safety advantages. The steel shell developed allows eliminating the heavy full cast iron design to keep cast drums from breaking. It absorbs energy by converting friction between the drum surface and lining into heat. Heat must be stored and then quickly dissipated to prevent the loss of stopping power as well as drum and lining deterioration. The unique ribbed steel shell provides not only strength, but also additional surface area to dissipate heat. It also reduces excessive cast iron mass. Full cast drums must be provided with

Fig. 2.4 Steel shell cast iron composite drum

additional iron in the drum band and mounting areas in order to achieve the same strength. The steel drum back contributes to significant weight savings that result in increased payloads and improved fuel economy. The composite drum is developed out of a need to reduce the weight of passenger cars and light trucks.

The composite drum is produced by stamping a steel drum back and placing it into a mold at the foundry. Molten iron is poured into the mold and fills the cavity to take the shape of the drum pattern. As the molten iron solidifies, the steel drum back fuses with the cast iron at the edges. The steel shell cast iron and its cross section are shown in Figs. 2.4 and 2.5 respectively. A mechanical bond is also formed from tabs created during the stamping process. The composite drums require less machining than full cast drums. Typically, only the brake surface and the open lateral surfaces are machined, thereby reducing cost. A weight reduction of 10–15 % over full cast is achieved.

2.2.4 Steel Cage Reinforced Cast Iron Brake Drum

The steel cage reinforced cast iron drum incorporates two rugged materials, steel and cast iron, into one composite reinforced structure that resists checking and cracking without increasing mass. Figure 2.6 shows a reinforcing steel cage that provides strength and prolongs life of the brake drum. This steel cage is comprised of hoops and crossbars for superior radial strength and additional axial stability. There is less deflection and mechanical stress, because the steel takes the brunt of the braking load. So the drum is less sensitive to heat checking that leads to cracking and eventual breakage of the drum. In highway truck/trailer brake applications where good thermal conductivity is essential, there is no substitute for

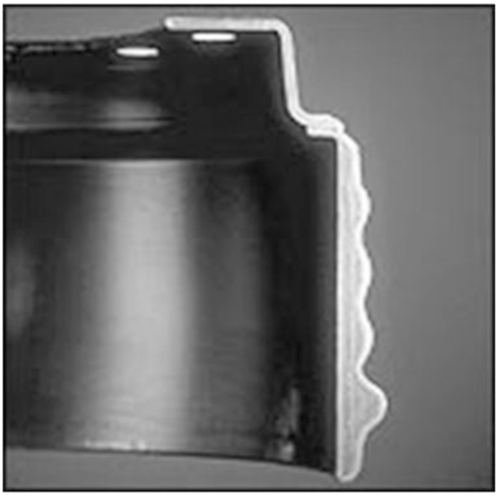

Fig. 2.5 Cross section of brake drum

cast iron. The inner steel cage of brake drum is literally surrounded by cast iron providing excellent heat absorption throughout the drum while improving strength and drum life. The machined mounting face of the cast drum provides a solid supporting foundation for the wheels of the vehicle. This rigid mounting face assures a completely flat mating surface for positive wheel support.

2.2.5 Fly Ash Reinforced al MMC Brake Drum

The MMCs reinforced with fly ash have the potential of being cost effective, light weight composites with good mechanical properties. These composites are

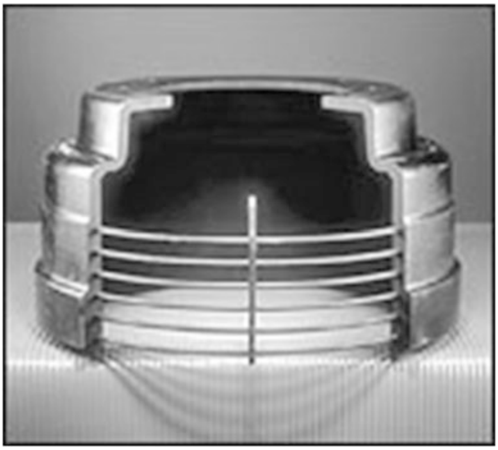

Fig. 2.6 Steel cage reinforced drum

Fig. 2.7 Fly ash reinforced brake drum

manufactured by dispersing coal fly ash in aluminium alloys. These composites offer cost saving low energy consumption and light weight. The Fig. 2.7 shows a fly ash reinforced MMC brake drum manufactured and studied in University of Wisconsin-Milwaukee. But the limitations are the segregation of low density fly ash composite, and mixing of this low density fly ash with the aluminium alloy.

2.2.6 Silicon Carbide Reinforced Copper MMC

The Metal Matrix Composites of copper alloy reinforced with silicon carbide particles are more suitable for use in brakes and other severe frictional applications because of their higher thermal conductivity, higher melting point and superior corrosion resistance. Kennedy et al. (1997) have investigated the tribological characteristics of copper based silicon carbide particulate metal matrix composites synthesized from copper coated silicon carbide particles. They performed wear tests using pin on disc method and compared the wear resistance and friction coefficient with the cast iron while sliding against friction material. They have observed that the Cu based MMCs have better wear resistance and the friction coefficient is comparable with the cast iron. The increase in wear resistance is because of the presence of the hard SiC particles in the copper matrix.

2.2.7 Thixoformed Hypereutectic Aluminium Silicon Alloy

Solidification of hypereutectic Al–Si alloys contain primary silicon particles which provides cast parts with a in situ composite structure which resembles that of a

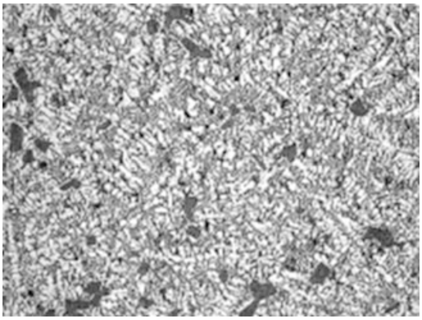

Fig. 2.8 Cast Al–Si alloy

Fig. 2.9 Thixoformed alloy

Fig. 2.10 Thixoformed brake drum

particulate MMCs reinforced with silicon inspite of silicon carbide particles as shown in Figs. 2.8 and 2.9. The resulting material has improved properties like high wear resistance, high strength and high hardness. Kapranos and Kirkwood (2003) have thixoformed an automotive brake drum using A390 hypereutectic alloy and bench tested at room temperature, 200 and 350 °C. They have found that the thixoformed drums had good thermal and wear properties when compared to cast iron drums. The drum has less weight and good wear resistance. The Fig. 2.10 shows the thixoformed brake drum.

2.2.8 Carbon/Carbon Composites

The carbon/carbon brakes are manufactured from carbons of different structural characteristics such as PAN carbon fibers and vapor deposited carbon. These composites have good thermal shock resistance, high thermal conductivity and high strength at elevated temperatures. The heat capacity is 2.5 times more than steel. The development of these materials and manufacturing technologies is underway. Blanco and Bermejo (1997) have presented the structure, properties, applications and operational behaviour of carbon-carbon disc brakes. They have investigated the wear, role of friction, dust, friction and lubrication and the mechanisms of wear. Zaidi and Senouci (1999) have studied the friction behaviour of carbon brake block/brake drum system at high sliding speed under high applied load. The contact temperature, friction behaviour and temperature evolution are determined. They have studied the mechanical and thermal damages caused under high dynamic load.

2.3 Design and Optimization of Brake Drum

Literatures are available on the general optimization procedures (Arora 1989; Rao 1995). Rajendran and Vijayarangan (2001) formulated a solution technique using genetic algorithm for design optimization of composite leaf spring. On applying the GA, they have obtained optimum dimensions for the composite leaf spring, which contributes towards achieving the minimum weight with adequate strength and stiffness. Rangaswamy and Vijayarangan (2005) have established a model to optimize the parameters of the composite drive shaft to reduce the weight of the composite drive shaft using genetic algorithm. They have achieved a considerable weight saving and the variation of the stress is also found to be within the permissible limit. Wang et al. (1999) have developed a method for shape optimization process to enable the description of the shape. Genetic algorithms are nontraditional optimization process based on the mechanics of natural genetics and natural selection of parameters. The fundamentals of genetic algorithm are explained by Raol and Jalisatgi (1996). Deb (1991) has developed the computer algorithm of GA. Goldberg (1989) has termed the operation procedure of GA as working with a coding solution, search from a population, and use probabilistic transition rules. Sandgre and Jense (1992) have suggested a new approach for the design and optimization of structural components. The permissible design space is discretized with each element assigned a design variable, which determines how it modifies the design. A generic optimization is applied to turn each element either on or off and penalty function is employed to handle design constraints stress and maximum deflection. Rajeev and Krishnamoorthy (1992) have discussed a simple genetic algorithm for optimizing structural systems with discrete design variables. Deb (1991) has used genetic algorithm to optimize welded beam structure consisting of a highly nonlinear objective function with five nonlinear constraints. Botello et al. (1999) have used genetic algorithm and simulated annealing to the optimization of pin-jointed structures. Wellman and Gemmill (1995) have applied the genetic algorithms to the performance optimization of asynchronous automatic assembly systems and the performance of genetic algorithm is measured through comparison with the results of stochastic quasi-gradient methods to the same automatic assembly systems. Duda and Jakiela (1997) have explained how the genetic algorithm is used to distribute subsets of the evolving population of solutions over the design space. Cunha et al. (1999) have presented the use of genetic algorithms as a complementary technique allowing a fist estimation of elastic coefficients. Cho and Gweon (1999) have suggested a new kind of static estimator based on genetic algorithms based on search technique.

The literature surveys carried out have shown that the optimization technique can be applied to optimize the design of components. Although many papers are available on optimization of engineering components no paper has been reported in the field of optimization of brake drum.

2.4 Manufacturing of Metal Matrix Composite

Ding et al. (2000) have designed and manufactured a front brake rotor by semi-sold stirring plus liquid forging process. Then the brake rotors are subjected to dynamometer test and the performance of the MMC brake rotor is compared with the conventional cast iron rotor. They have concluded that the MMC rotors have higher wear resistance, low temperature rise, high friction coefficient. Pai et al. (2001) have presented the low cost processing of MMCs, surface treatment of reinforcement, process parameters and the role of alloy additions with the special reference to the Al-graphite system, Al-silicon carbide, and Al-short fibers carbon systems. They have also highlighted the manufacturing of MMC components like piston rings, pistons, cylinder sleeve and connecting rods for light weight automotive applications. Pillai et al. (2001) in their investigation, they have concluded that the semisolid processing of aluminium composites have better properties like minimum interfacial reactions, uniform distribution of reinforcements and high percentage of reinforcement can be added with the matrix alloy. Degischer and Prader (2000) have presented the functions of thematic network in assessing the applications of metal matrix composite materials in all technical fields. They have also presented the role of the thematic network in sharing information on processing, testing, modeling, application and marketing of MMCs. Goni et al. (2000) have suggested that the high processing cost of MMCs, as the important barrier for using it in automotive applications. They have also suggested that the cost of MMC components can be reduced either by locally reinforcing the reinforcement or by reinforcing the MMC inserts in the required positions of the automotive components. Degischer et al. (2001) have presented the functions of thematic network in developing the processing and applications of MMCs. They have also presented the activities of the thematic network in sharing information on processing, testing, modeling, application and marketing of MMCs.

2.5 Wear Analysis

The wear and friction measurements have been proposed by various researchers (Anderson et al. 1984; Ludema 1992). Deuis et al. (1997) have presented a review on the dry sliding wear of aluminium composites. The friction and wear mechanisms of aluminium composites and the influence of applied load, sliding speed, wearing surface hardness, model for wear volume and the role of reinforcement phase are also have been presented. Tjong et al. (1997) have conducted wear tests on compo-cast aluminum silicon alloys reinforced with low volume fraction of SiC. Based on the wear test conducted on the block on ring, they have concluded that the addition low volume fraction of SiC particles is an effective way of increasing the wear resistance of the matrix alloy. Kwok and Lim (1999) have investigated the friction and wear behaviour of four Al/SiC_p composites over a wide range of sliding conditions by the use of a specially adapted high speed tester of the pin on disc configuration. Their investigations have shown that the wear rate increased with applied load, but varied in a rather complex manner with speed. The increased wear rate is due to catastrophic failures and melting of composites at higher loads and speeds.

Kwok and Lim (1999) have documented their investigations into the various mechanisms of wear as abrasive and delamination wear, a combination of abrasion, delamination, adhesion and melting. The size of reinforcement controls the high speed wear resistance of composites tested and concluded that the small SiC particles are more suitable for lower speed applications. Berns (2003) has compared the microstructures of conventional white cast irons and new metal matrix composites. Based on their instigation on wear resistance, toughness, corrosion resistance and fracture toughness, they have concluded that the replacement of MMC for the conventional cast iron in applications like ear protection components in the mining and cement industry where the abrasion by mineral grains prevails is feasible. Yang (2003) has developed a new formulation of wear coefficient and tested experimentally. He has conducted two different types of pin on disc wear tests using three commercial aluminium based metal matrix composites. Hardened steel disc is used as the sliding counterface for the MMC pins having 10, 15 and 20 % alumina reinforcements. He has derived a new wear equation based on exponential transient wear volume equation and Archard's equation and proved that they are better predictor of steady state wear coefficients.

Martin et al. (1996) have studied the influence of temperature on the wear resistance of 2618 Al alloy reinforced with 15 vol% SiC particulates and the corresponding unreinforced alloy in the temperature range 20–200 °C. They have concluded that the addition of the SiC particulates improved the wear resistance by a factor of two in the mild wear region due to the retention of mechanical properties of composites at elevated temperatures. Rohatgi et al. (1992) have developed a theoretical model to describe the steady sliding wear in a system of an alumina particle reinforced aluminium metal matrix composite pin on steel disc. The model predicts that the volumetric wear of the pin on disc system is proportional to the applied load, and depends on the particle volume fraction of the applied load, and depends on the particle volume fraction of the composite and relative hardness of the rubbing pair. They compared the theoretical results with the experimental results and found a good agreement between the experimental and observed results. Sahin (2003) has investigated the wear behaviour of aluminium alloy and its composites by means of pin-on disc type wear rig. He has carried out abrasive wear tests on 5 vol% SiCp and its matrix alloy against SiC and Al_2O_3 emery papers on a steel counter face and expressed the wear rate in terms of applied load, sliding distance and particle size using a linear factorial design approach. He has observed that composite exhibited low wear rate compared to unreinforced matrix material in both cases and conclude that the factorial design of an experiment can be successfully employed to describe the wear behaviour of aluminium alloy and its composites. Eriksson and Jacobson (2000) have studied the formation, mechanical properties and composition of the tribological surfaces such as organic brake pads sliding against grey cast iron rotor using high resolution scanning electron microscopy. They have presented the coefficient of friction, nature of contact, formation of contact plateaus. Eriksson et al. (2002) have presented the tribological contact in cast iron discs involving dry sliding contact at higher speeds and high contact forces. They have also presented the variation of contact surface and the corresponding variation of the coefficient of friction. Ostermeyer (2003) has presented the principal wear mechanism in brake systems by introducing a dynamic model of the friction coefficient by including both friction and wear. He has presented the characteristic structure formed in the contact area, the friction coefficient based on the equilibrium of flow of birth and death of contact patches. The dependence of the friction coefficient on the temperature and the fading effect of the brake system are also presented by him.

Shorowordi et al. (2004) have investigated the velocity effects on the wear, friction and tribochemistry of aluminium metal matrix composites sliding against phenolic brake pad. reinforced with 13 vol% of SiC made by stir casting followed by hot extrusion. They have concluded that higher velocity leads to lower wear rate and lower friction coefficient for both MMCs. It is also suggested that the transfer layer on MMC acts as a protective cover and helps to reduce both wear rate and friction coefficient. Straffelini et al. (2004) has investigated the effect of load and temperature on the dry sliding behaviour of Al based MMCs sliding against friction material. The dry sliding tests are carried out in a block on disc configuration by using MMC as disc material and friction material as the block. High temperature tests are carried out at three load levels, namely 500, 650 and 800 N. Heating is carried out by means of two thermo resistances. They have concluded that for loads lower than 200 N the wear is less where as the friction coefficient is quite high, around 0.45 and for loads more than 200 N the contact temperature becomes more than 150 °C and the friction decreases and wear increases. Howell and Ball (1995) have investigated the wear mechanisms of two magnesium/silicon aluminium alloys each reinforced with 20 vol% percentage SiC particulates sliding against three makes of automobile friction material. Two of the friction linings are commonly used against cast iron rotors in automobile brake systems while the third has been specifically formulated for use against aluminium metal matrix composite brake rotors. In the conventional friction material, the wear occurs through a process of three body abrasion. In case of specifically formulated friction material for use against MMC rotor wear has been found to be low. By their investigation, they have concluded that if the structure and composition of the friction linings are arranged correctly, the wear resistance and frictional performance of aluminium MMC brake rotors are superior to those of cast iron rotors. The wear of materials at high temperature and the transfer films have been investigated by various researchers (Liu 1980, 2004; Celik et al.2005; Sallit et al.1998).

2.6 Testing of MMC for Brake Drum Applications

Valente and Billi (2001) have developed an innovative test apparatus to induce cyclic thermal stresses in MMC specimens. The modification induced and the residual properties of the specimens are then investigated through mechanical tests and fractographic analysis. Their results have showed that MMC has good resistance to thermal cycling at least at the maximum temperature of 300 °C. They have concluded that the possibility of employing this material to car braking is good and suggested further investigations. Guner et al. (2004) have developed a cost effective approach to investigate brake system parameters. They have investigated the dynamic and thermal behaviour of the braking phenomenon by establishing a dynamic model. They have used the Newmark integration scheme and predicted the stopping distance and speed and verified these using test results. They have also conducted thermal analysis and found an excellent agreement between the numerical and test results. Roberts and Day (2000) have established a new systematic approach to design-evaluation-test product development cycle wherein the vehicle design and simulation environments are integrated. By implementing virtual testing early in the product development cycle has the potential to shorten development time, reduce risk of failure during expensive physical testing, and increase the overall product quality. Limpert (1999) has developed models for determining the temperature rise during single stop, continuous and repeated braking. Ramachandra Rao et al. (1993) have simulated the temperature distribution and brake torque developed in a brake drum using finite element methods. They have observed a good agreement between the simulated results and the observations carried out using an inertia dynamometer. Ilinca et al. (2001) have determined the effect of contact area on the temperature distribution in brake drum which results in wear and deformation of brake drum.

2.7 Summary

The literature survey carried out has shown that only few papers are available about the applications of Al MMCs. No paper has been reported in the following fields for using the Al MMCs for the brake drum applications. Hence, it has been decided to carry out the above studies to evaluate the suitability of Al MMC for light weight automotive brake drum applications.

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