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METAL MATRIX COMPOSITE BRAKE ROTOR: HISTORICAL DEVELOPMENT AND PRODUCT LIFE CYCLE ANALYSIS

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ABSTRACT

Metal matrix composites (MMCs) have become attractive for engineering structural applications due to their excellent specific strength property and are increasingly seen as alternative to the conventional materials particularly in the automotive industry. In this study, a historical background on the development and application of metal matrix composite for automotive brake rotor is presented. The discussion also includes analysis of the product life cycle with stir casting as a case study. The historical review analysis revealed that gradual development of material and processing technique have lead to a lighter weight, lower cost, and higher performance brake rotor as a result of the better understanding of the mechanics of metal matrix composite. It emerged from the study that stir casting technique provides ease of operation, sustainability and most significantly very competitive without sacrificing quality relative to other techniques; and as such is the most attractive manufacturing process in the industry. These findings can be used for future design and manufacture of an efficient and effective aluminium matrix composite brake rotor for automotive and other applications.

Keywords: metal matrix composite; brake rotor; product life cycle; historical development

INTRODUCTION

For the past 40 years, materials design has shifted emphasis on pursuing light weight, environment friendly, low cost, quality, and better performance materials. Parallel to this trend, metal-matrix composites (MMCs) have been attracting growing interest for many applications (Kaczmar et al., 2000; Rohatgi et al., 1992; Chawla, 1992). MMCs attributes include improved performance in the mechanical behaviour (e.g., tensile and compressive properties, and tribology) and physical properties (e.g., density, thermal expansion, and thermal diffusivity) by varying the weight fraction of the reinforcement phase. However, the low ductility property and low-transverse creep resistance developed due to the hard particulate reinforcement is the major drawback that limits the usage in structural component applications. A substantial research effort has been directed towards developing an improved understanding of their potential and limitations invoking principles of physical metallurgy, stress analysis, processing sciences and applications.

In recent years, the development of MMCs has been receiving worldwide attention on account of their superior strength and stiffness in addition to high wear resistance and creep resistance comparison to their corresponding wrought alloys. Metal-matrix composites have been used commercially in the automotive market for nearly 20 years. Properties of interest to the automotive industry include increased specific strength and stiffness, wear resistance, thermal conductivity and improved high-cycle fatigue resistance (Allison and Cole, 1993). Weight savings is also important in automotive applications with the need for achieving performance improvements with much lower-cost materials and processes. There has been successful application in several automotive applications in which the combination of properties and cost satisfied a particular need. As a result of these successful applications, business communications company (BCC), Inc (www.bccresearch.com) estimates that the global market for metal matrix composites consumed 4.1 million kilograms of materials in 2007 and 4.4 million kilograms in 2008. This is expected to increase to 5.9 million in 2013, for a compound annual growth rate (CAGR) of 5.9%. The ground transportation segment has the largest share of the market and used 2.4 million kilograms of materials in 2008. This should reach 3.2 million kilograms in 2013, for a CAGR of 5.5% (Swift, 2009). Figure 1 shows the global metal matrix composite by application and segment.

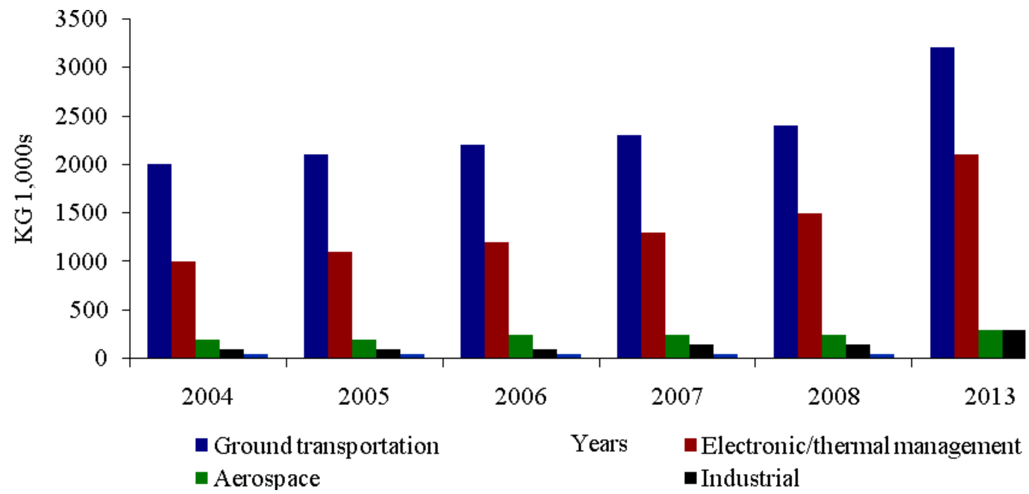

Figure 1. Global MMC outlook by application/segment, 2004 – 2013
[http://www.bccresearch.com/report/AVM012D.html]

In automotive application, brake rotors have been held up as an example where MMCs make a difference. In terms of weight, MMC rotor designs provide up to a 60% reduction when compared to cast iron. In addition, aluminum MMC rotors outperform their iron counterparts in terms of their mechanical properties and practical use. It has been found that the value of weight reduction in the automotive industry is between \$0.35- \$3.50/kg depending on vehicle platform. Therefore, a 7-kg-iron rotor produced in aluminum MMC at 50% the weight could result in a savings of \$ 1.23- \$12.25. In a comparison of an aluminum MMC brake rotor vs. an iron brake rotor, the iron component will be the higher value in terms of purchase price, post-purchase processing and maintainability, but the MMC component wins out in terms of performance, marketability and maintainability (Bruski, 2000).

HISTORICAL REVIEW OF BRAKE ROTOR

Brake rotor development and its use began in England in the 1890s. The first caliper-type automobile brake rotor was patented by Frederick William Lanchester at Birmingham, UK in 1902 and used successfully on Lanchester cars. However, the limited choice of metals in this period resulted to the use of copper as the braking medium acting on the rotor. Major advancement in brake technology came in 1918 with the invention of four wheel hydraulic brake systems by Malcolm Loughead. The hydraulic brake system replaced the mechanical brake system that was in use at this time. The mechanical system had numerous disadvantages which made it difficult to brake all the wheels evenly, often causing a loss of control. Moreover, it required drivers to exert tremendous amounts of force on the brake pedal to slow the car. The hydraulic brake system multiplied the force that was applied to the brake, lessening the amount of force needed to be applied to the brake pedal by the driver. This system was first used in 1918 by Duesenberg, by 1929; four wheel hydraulic braking systems were standard equipment on modern cars. Modern-style brake rotors first appeared on the low-volume Crosley Hotshot in 1949, although they had to be discontinued in 1950 due to design problems which significantly affect the life cycle of the brake rotor.

Aluminum matrix composites were first developed to meet very high performance needs for structural applications. Continuous fiber reinforced aluminum was used in the Space Shuttle and Hubble Space Telescope, material cost became a more significant consideration and emphasis shifted toward particulate-reinforced materials, with the goal of a lower cost, high volume product that could be used in automotive and commercial aerospace applications. Major aluminum companies, had metal matrix composites development programs in the 1980's and early 1990's. Alcan, through its Duralcan subsidiary, established a 36 million USD per year production capability for particulate-reinforced aluminum composites (Rittner, 2000). Automotive applications include cast aluminum composite brake drums and rotors on the Prowler and EV-1, driveshafts for the Corvette and GM S/T truck, and tire studs in Scandinavia. In the aerospace field, aluminum composites are used in the fan exit guide vanes of the Pratt and Whitney 4000 series engines, which power the Boeing 777. Another exciting area of application for aluminum composites is in the fast-growing electronics packaging market, primarily for thermal management (as shown in Figure 1) applications in which the ability to match the coefficient of thermal expansion of the electronic materials is a key attribute.

Metal-matrix composite brake rotors and drums are typically produced by casting processes such as semi permanent gravity casting. Aluminum-magnesium and aluminum-silicon matrix alloys and both SiC and Al_2O_3 particle reinforcements have been used, typically of at least 20% by volume. A number of automobiles now use MMC brake components. The Lotus Elise used four discontinuously reinforced aluminum (DRA) brake rotors per vehicle from 1996 to 1998, and the specialty Plymouth Prowler has used DRA in the rear wheels since production started in 1997. Discontinuously reinforced aluminum rotors are particularly attractive in lightweight automobiles and are featured in the Volkswagen Lupo 3L and the Audi A2. In addition, a number of electric and hybrid vehicles, such as the Toyota RAV4, Ford Prodigy, and the General Motors Precept, are reported to use MMC brake components (Miracle and Hunt, 2004). Figure 2 shows a selection of discontinuously reinforced aluminum (DRA) brake rotors.

Figure 2. Discontinuously reinforced aluminum MMC brake rotors
[http://www.mmc-assess.tuwien.ac.at]

MMC BRAKE ROTOR APPLICATION

Aluminium-based MMCs offer a very useful combination of properties for brake system applications in replacement of cast iron. Specifically, the wear resistance and high thermal conductivity of aluminum MMCs enable substitution in disk brake rotors, with an attendant weight savings on the order of 50 to 60%. Because the weight reduction is unsprung, it also reduces inertial forces, providing an additional benefit in fuel economy. In addition, lightweight MMC rotors provide increased acceleration and reduced braking distance. It is reported that, based on brake dynamometer testing, MMC rotors reduce brake noise and wear, and have more uniform friction over the entire testing sequence compared to cast iron rotors (Miracle and Hunt, 2004). Table 1 shows the advantages of metal matrix composite over metals and other composites (Chawla and Chawla, 2006)

Table 1. Advantages of metal matrix composites (MMC) over metals and other composite (polymer matrix composites PMC)

Metals	Other composites
Major weight savings due to higher strength-to-weight ratio	Higher strength and stiffness
Exceptional dimensional stability (for example, SiC,/Al to Al)	Higher thermal conductivity and service temperatures
Higher elevated temperature stability, i.e., creep resistance	Higher electrical conductivity (grounding, space charging)
Significantly improved cyclic fatigue characteristics	Better transverse properties and radiation survivability (laser, UV, nuclear, etc.)
Better wear resistance	Improved joining characteristics

Aluminum is utilised as the most popular matrix for the metal matrix composites (MMCs). The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity. They are usually reinforced by SiC, Al_2O_3, C but TiB_2, BeO, BN, B_4C, SiB_6, Cr_3C_2, Gr, TiB, TiC, Si may also be considered. From previous study (Andreas, 2007) it was found that the usage of matrix and particle reinforcement materials by companies varies, Figures 3 and 4 indicate that most company uses aluminium as matrix material and SiC as particle reinforcement respectively.

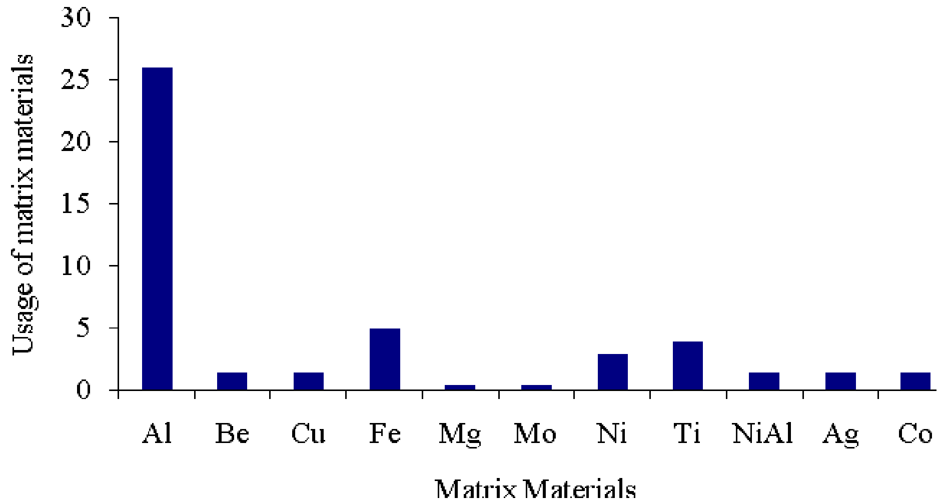

Figure 3. Usage of matrix materials

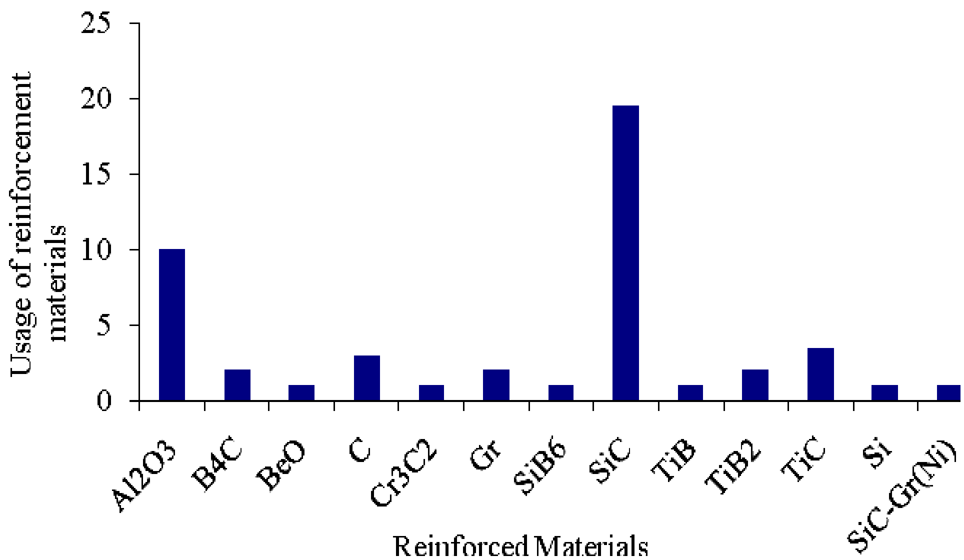

Figure 4. Usage of particulate reinforced materials

PRODUCT LIFE CYCLE ANALYSIS

The life cycle of a product is the length of time between its introduction on the market for the first time and the time when the production declines or decides to stop. The interval between the introduction and decline stage witnesses the growth and maturity stages of the product and it varies from few months to several years depending on its nature, usefulness, competition, environmental impact as well as technological development. The automotive industries have a relatively short life cycle as a result of fast technological development, pressure due to competition are also high due to advanced research and development. Automobile parts (piston, push rods, connecting rods, drive shaft, and brake systems) have witnessed advancement in materials and manufacturing processes which in turn has influenced the life cycle analysis.

Brake rotor life cycle

The life cycle of an automotive brake rotor begins when it is introduced into the market after product development. This gives opportunity for new product as a result of material development and better processing technique. Initially sales grow slowly at the introduction stage when the MMC brake rotor is new on the market due to the limited awareness of its performance and improved properties. Sales subsequently rise rapidly during the period of growth with the acceptance of an increasing number of customers as the market stabilises, then the product MMC brake rotor becomes mature. As the brake rotor reaches maturity, it is overtaken by new developments with the introduction of superior competitors. At this period it experiences a decline and may be eventually withdrawn when new design modification with new materials and manufacturing processes is not developed to prolong the life cycle. From Figure 5, it can be seen that brake rotor life cycle consist of four different stages such as introduction, growth, maturity and decline.

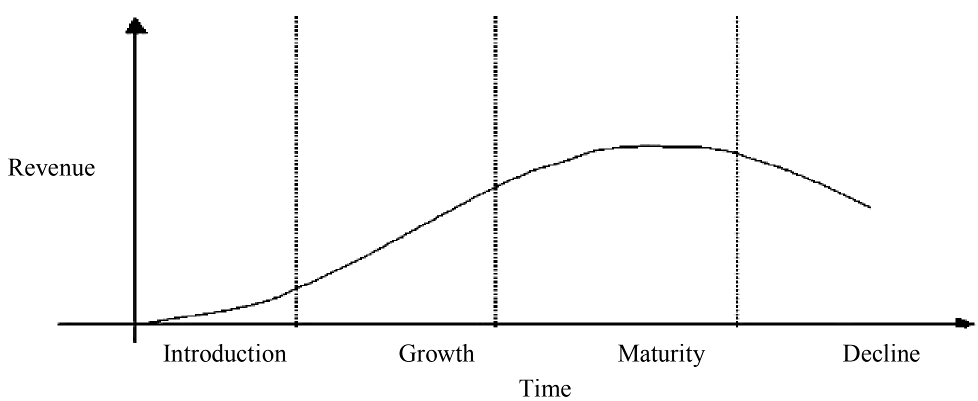

Figure 5. Automotive brake rotor life cycle

Introduction Stage

At the introduction (or development) stage market size and growth is slow. Substantial research and development costs have been incurred in getting the MMC brake rotor to this stage. In addition, marketing costs may be high and it is unlikely that companies will make profits on newly developed products at this stage. The newly developed brake rotors are carefully monitored and advertised to ensure that they start to grow. Otherwise, the best option may be to withdraw or end the product. The need for immediate profit is not a pressure as the lack of it is expected at this time. The superior mechanical and thermal performance is promoted to create awareness. If the MMC rotor has no or few competitors, a skimming price strategy is employed to maximise profits. Limited numbers of product will be available in few channels of distribution. Figure 6 shows the profit and loss for the product life cycle of brake rotor and it clearly illustrates that heavy costs is incurred for research and development before the launch of the MMC brake rotor. This is a negative cash flow and great effort is usually applied to minimise this expenditure.

Growth Stage

The growth stage is characterised by rapid growth in sales and profits as the product is becoming established. Profits arise due to an increase in output (economies of scale) and possibly better prices for raw materials and manufactured components. Competitors are fewer, sales are growing and profit margins are good. At this stage, it is cheaper for company to invest in increasing their market share as well as enjoying the overall growth of the market. Competitors are attracted into the market with very similar offerings. Advertising cost becomes high and focuses upon developing product brand such as ventilated and solid brake rotors with various design concepts.

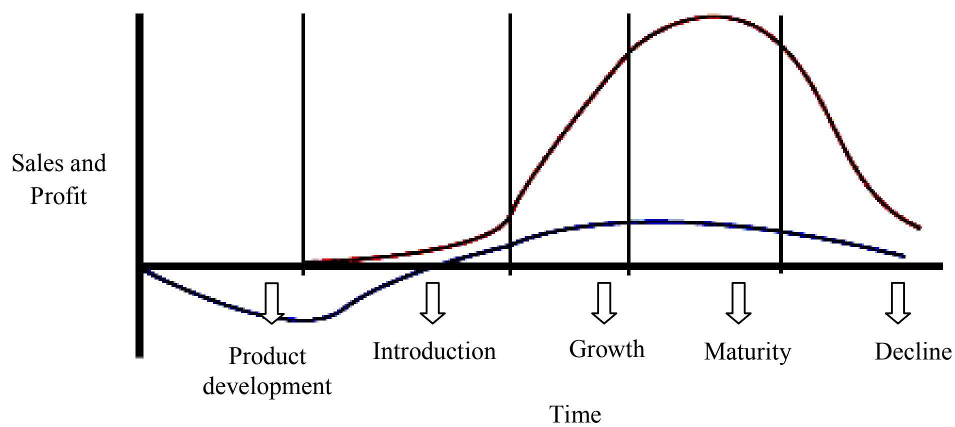

Figure 6. Profit and loss for the product life cycle of automotive brake rotor

Maturity Stage

It is in the stage where competition is most intense because the production rates are most efficient, the investment used in the MMC brake rotor development is recovered, and most profits are made. In order to prolong the maturity stage, efforts should be made to develop new design modification with new materials and manufacturing processes for the MMC brake rotor and also adopting new marketing strategies. Introducing an improved version of the brake rotor can also prolong its life cycle. This will improve efficiency or extend the use of the product to new applications and environments. Improving fuel economy by reducing weight, reducing aerodynamic drag forces, or improving the efficiency of the engine can extend the maturity stage.

Decline Stage

At this stage, as a result of the appearance of other competitive advanced material brake rotor, processing technique, or technological advances the MMC brake rotor may become less competitive causing the sales to decrease and the rotor to reach the decline stage. From the above study it is not sufficient to design and manufacture a successful brake rotor. Researchers and engineers should continue to improve the effectiveness and efficiency of the brake rotor by making use of new technologies in order to improve the performance of the rotor.

STIR CASTING OF ALUMINIUM METAL MATRIX COMPOSITE

Stir casting is a unique and prominent technique for the development of reinforced aluminium matrix composite materials. This technique is utilized as a result of its simple process and ability to overcome the problem of expensive processing method which has restricted the widespread application of metal matrix composite which are considered potential material candidate for various structural and non structural applications in the field of aerospace, automotive, biomedical, military defence and sports industries. The development of this promising technique evolved as a result of modern technological advancement in material application and the demand for light weight materials with improved mechanical and thermal properties. This process involves a liquid state fabrication technique which requires the incorporation of reinforcing phase (discontinuous form) into a molten matrix metal (continuous form) to obtain a uniform distribution through stirring as shown in Figure 7.

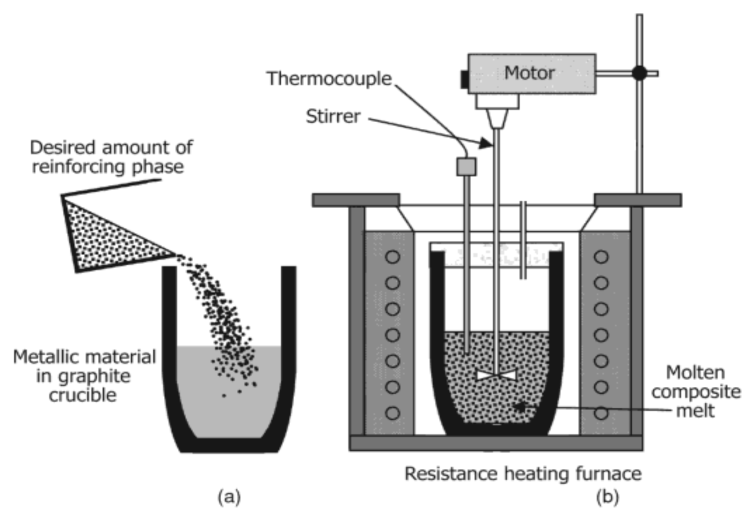

Figure 7. A schematic diagram showing (a) incorporation of reinforcing phase into matrix metallic material (b) the stir casting setup (Gupta and Sharon, 2011).

Ibrahim et al. (1991) and Lloyd (1994) report that vortex-mixing technique for the preparation of ceramic particle dispersed aluminium matrix composites (AMC) was originally developed by (Surappa and Rohatgi, 1981) at the Indian Institute of Science. Subsequently several aluminium companies further refined and modified the process which are currently employed to manufacture a variety of AMCs on commercial scale in various industries. The cost of production is about one-third (Skibo and Schuster, 1988) to half compared to other competitive methods such as centrifugal casting and powder metallurgy for large volume production. It is also anticipated that the cost of production will fall to one-tenth with further research and development. Figure 8 shows the material flow process for MMC brake rotor production using stir casting process.

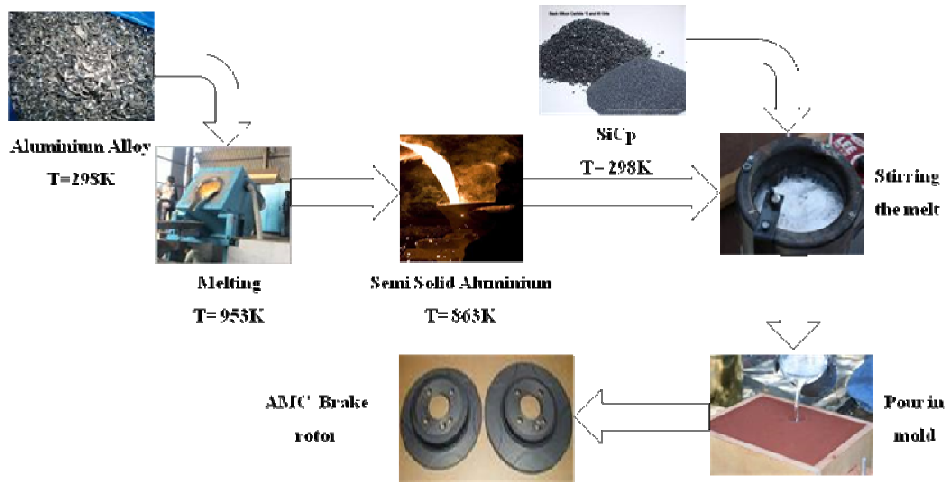

Figure 8. Material flow process for MMC brake rotor production

From Figure 8, the aluminum alloy was heated up to 953 K in a resistance-heated furnace. The molten metal is transferred to a graphite crucible in a semi solid state and the silicon carbide particles were added. The mixture was then stirred to optimize uniform particle distribution into the melt. After stirring, the mixture was reheated and the developed composite was poured into a mold for solidification. The final product gives the fabricated desired product AMC brake rotor.

CONCLUSION

The following conclusions can be drawn from the present study;

a. The historical development revealed that there was a gradual development of material and processing technique for aluminium metal matrix composite.
b. The stir casting technique for aluminium matrix composite brake rotor is better than other technique because it provides ease of operation, higher performance and better quality.
c. Developing new design modification with advanced materials and manufacturing processes prolong the life cycle of the MMC brake rotor.
d. Reviewing the present development gives opportunity for further improvement of the aluminium matrix composite brake rotor.

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