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A low cost, light weight cenosphere–aluminium composite for brake disc application

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Abstract. **The commonly used composite material for brake rotor consists of silicon carbide (SiC) or aluminium oxide (Al_2O_3) particles which are more expensive. The weight of conventionally used composite is more compared to base alloy. The aim of this paper is to develop a light weight material for brake disc applications thereby substituting base alloy and conventional composite. This analysis led to 10 vol% cenosphere reinforced aluminium alloy (AA) 6063 composite as the most appropriate material for brake disc. To ensure the manufacturability of composite, composite brake rotor was casted using the sand casting technique and was machined to achieve the final component. Thermal capability of brake disc was ensured by studying temperature variation through vehicle testing procedure of disc brake. Cost reduction is one of the important benefit acquired using cenosphere reinforced composite. This was ensured by cost estimation and analysis. The cost estimated to manufacture the AA6063 brake disc was compared with composite cost.**

Keywords. **Brake disc; aluminium composite; temperature measurement; cost estimation.**

1. Introduction

During the past decade, conventional metal matrix composites have been used in several automotive applications, including brake rotors and drums, pistons, cylinder liners and valves. The composite brake drums and rotors have been limited to low volume, specialized applications, due to the high cost of the composite materials. As a replacement for drum brakes, the disc brakes command great significance in automobile industries and indispensability in aeronautical industries. Further research towards improvement led to the use of composites due to their low weight and high thermal characteristics. The need to reduce weight and improve fuel efficiency has made aeroindustries to extensively use aluminium composites in recent years.

The commonly used aluminium composite for these applications is the aluminium alloy-based metal matrix with ceramic particle reinforcement, which are considerably more expensive than the ceramic particles derived from flyash [1]. Material costs exclusive of mixing and processing costs for cenosphere composites are very favourable compared to conventional Al–SiC materials. Due to the low cost of cenosphere particles, the overall cost drops sharply with increasing reinforcement content. Their comparative lower density to conventional grey cast irons results in reduction of weight upto 20% in their applications. This study analyses a new composite material called cenosphere reinforced aluminium alloy 6063. Its low thermal expansion and high endurance to hot and cold conditions makes it suitable for disc brakes.

Optimal cost estimation improves the performance and effectiveness of a business enterprise as overestimation leads to loss of goodwill and market share while underestimation results in financial losses. Hence cost estimation plays a vital and crucial role in an organization for design and operational strategies and a key instrument in managerial policies and business decisions [2]. The overall cost and lead-time could be considerably reduced by devoting more resources for early identification and prevention of potential manufacturing problems through coherent product and process design. Initial cost estimation is essential and useful to make decisions on the choice of alternatives for geometric, material or process parameters. In this section, the cost of casted AA6063 was arrived and compared with cost of composite brake rotor.

2. Literature review

Disc brake is often used in automobile transmission system to halt a vehicle. Due to space constraint and performance requirement, disc brakes have fluctuating load characteristics, resulting in local stress and deflections. Of all the constituents of the vehicle, the brake system is most vital and needs to be maintained at frequent intervals [3]. It is important to design engineering components for infinite life. Unfortunately, in systems where parts are at intimate contact and relative motion, wear is inevitable making designs difficult to ascertain [4].

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The high temperature generated due to frictional heat affects the contact pressure distribution leading to thermo elastic instability at which concentration of contact load at small regions cause undesirable effects such as brake fade phenomena, local scoring, thermal cracking and vibration [5,6]. Difference in temperature distributions exist with different materials of rotors [7]. But the difference in the result of using pad material would be insignificant [8]. The brake pad design and vibrational behaviour depends on the temperature distribution in the frictional contact between brake disc and brake pad. The frictional force results due to the chemical and physical process caused by temperature in the contact zone [9]. The aluminium metal matrix composite would be a better choice of material with its ease of processing technique and characteristic advantages such as high thermal conductivity, high heat dissipation rate which minimizes the thermal elastic instability, brake fluid vapourization and thermally excited vibrations [10,11]. Properties of the composite vary depending on the bonding between matrix and re-inforcement which can be controlled by alloying the material suitable for disc brake [12].

The ventilation system in rotor provides better temperature dissipation [13,14]. The ventilated rotor reduces the temperature, stress and deformation [15]. The cooling process in vent rotor will decrease the maximum temperature raised [16]. The present study considered ventilated brake disc for investigation.

Cost estimation of any product is important and cost reduction in early stages, when the cost of such modifications is low [17]. In present study, the cost estimation was done to manufacture the AA6063 brake disc which was compared with composite.

2.1 *Cenosphere reinforced AA6063*

Various volume percentages of cenosphere were reinforced out of which 10% cenosphere addition resulted in good mechanical and tribological properties. To establish the suitability of the newly developed material for brake disc, it is imperative to determine and ascertain that the performance parameters are within the permissible limits when the brake disc was made of the proposed material, namely, AA6063 aluminium alloy with 10% cenosphere composite. The material properties of the newly proposed composite were obtained and are shown in table 1.

Table 1. Material properties of composite.

Properties	10 vol% Cenosphere–AA6063 composite
Density of the material (kg m^{-3})	2140
Poisson's ratio	0.33
Young's modulus (GPa)	83.70
Yield strength (MPa)	95
Ultimate tensile strength (MPa)	142.70
Thermal conductivity (W m^{-1} K^{-1})	250
Coefficient of thermal expansion (C^{-1})	20.46×10^{-6}

3. Manufacturing of disc brake rotor

The possibility of making smaller batches at very low cost makes sand casting advantageous than permanent mould casting. This in turn helps the manufacturers to create products at a low cost in addition to other benefits like very small size operations. In present study, sand casting was used to cast the brake disc. The essential steps in casting disc brake rotor like pattern making, mould preparation, furnace selection, etc., are discussed as follows. The pattern was made of wooden materials to meet the exact standard of construction, to last for a reasonable time and according to the quality grade of the pattern being built, so that they will continuously provide a casting with specified dimensions. It was also cost effective and reliable for using the pattern repeatedly.

Wooden pattern was prepared as per the design of the rotor with all required allowances. Coating was carried out on the pattern to achieve smooth surface on casting. Dry-sand core was prepared according to the design and coated to achieve smoother surface finish and greater heat resistance. Figure 1 shows the pattern and core used for brake rotor casting.

A mould used in sand casting was made out of the sand itself by using binders and by making use of the pattern to extrude the mould into the desired shape and size orientations. The area formed by the pattern plate/pattern bolster, the mould box and the filling frame called mould was filled by loose moulding sand. The filled sand was then put to compact by forcing compressed air from the back of the mould to the pattern and allowed to escape through vents in pattern plate. This made the sand to move intact improving compaction. At the subsequent pressing stage by means of a fixed or flexible pressure plate, a water cushion or a multi-platen press, the final strength was achieved. Depending on the optimum mould strengths required the pressure of the press and

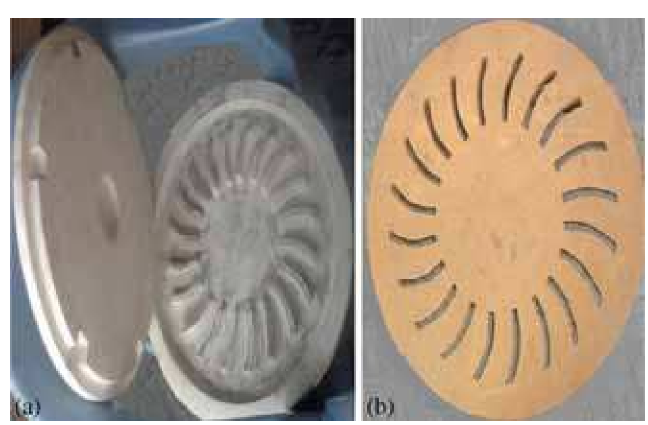

Figure 1. Disc brake rotor: (**a**) pattern and (**b**) core.

Figure 2. Preparation of sand mould for disc brake rotor.

Figure 3. Cenosphere to the molten metal: (**a**) addition and (**b**) stirring by hand stirrer.

duration of the air flow was controlled. The Seiatsu moulding process used to prepare the required sand mould for the brake disc is shown in figure 2.

Raw materials like AA6063, cenosphere and magnesium in required amounts were calculated and melted as per following procedure. The furnace used in this casting process was oil furnace with 30 l melting capacity. Oil furnace is well suited for the casting of the composite disc brake.

The stir casting method involves two stage mixing process. Initially the matrix material was heated to a temperature at which they are completely melted to a liquidus state. The calculated 2 wt% of magnesium was added during stirring to increase the wettability of cenosphere particles. Then melt was cooled down to maintain at a semi-solid state where the preheated cenosphere particles were added and mixed. The slurry was again heated to the liquidus state to have a thorough mix. The cenosphere addition and stirring process is shown in figure 3.

The molten metal was poured into the sand mould. After the mould has cooled, it was broken and the disc rotor was taken out after solidification of the molten mixture. The fabricated disc brake was machined to the exact dimensions, as the rotor had allowance while casting. The machining processes adopted to arrive the final component are described as follows.

3.1 *Facing inner and outer diameter*

The work centre chosen for the facing of the disc brake is 2 axis lathe. Obtaining a flat surface by pressing a tool across the end of the rotating brake disc is facing. The brake disc was held on a mandrel to avoid turning end to end and repeating the facing operation if both ends are to be faced. The highest diameter of the surface to be faced determines the cutting speed. The point of the tool was set exactly at the height of centre of rotation for both facing from outside inward or from centre outward. The carriage was clamped to lathe bed to avoid movement of tool due to cutting force and to prevent an unflat surface. Facing of materials that have hard surface such as castings and others requires sufficient penetration from the depth of the first cut to prevent tool wear. Both sides of disc were faced and surface finish within 16 μm was achieved.

3.2 *Drilling holes*

The work centre opted for drilling of disc brake is 3 axis medium mill. There were six holes with diameter 18 mm. A brake disc was located and centred in a mill vise. The step jaws provide clearance to drill without getting to the vise by locating brake disc off the bottom of the vise. The parallel bars were ensured to be of same size to have a flat position of the disc. Six holes were drilled in specified location. The fabricated disc brake before and after machining is shown in figure 4.

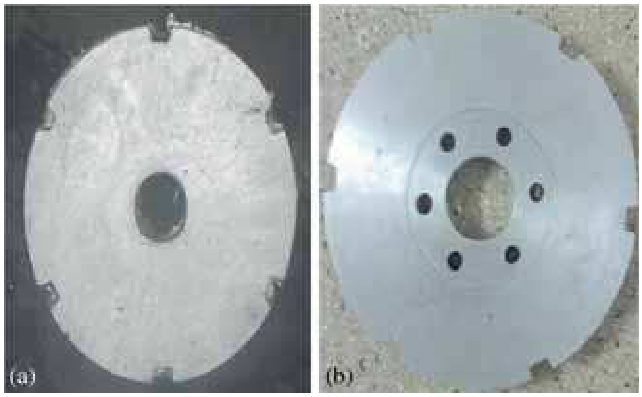

Figure 4. Casted disc brake rotor: (**a**) before machining and (**b**) after machining.

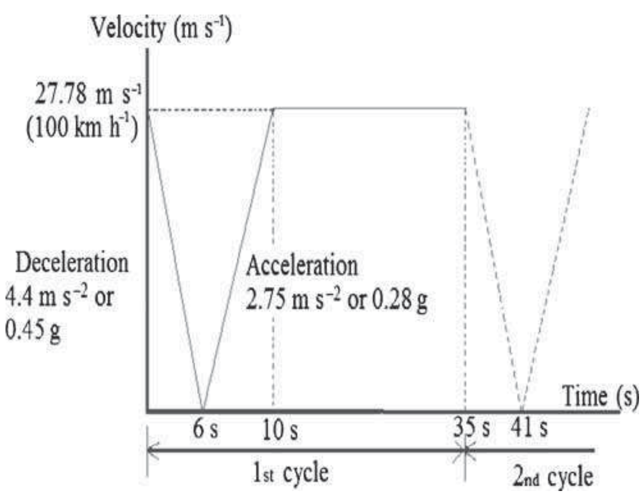

Figure 5. Huang YM load cycles.

4. Temperature measurement of composite brake disc

It is well known that the braking capability of brake disc is affected by the rate at which heat is dissipated. The rapid increase and decrease of the brake disc temperature could lead to catastrophic failure of the brake disc due to high thermal strains. Thermal characteristic enhancement in any ventilated disc design is of important interest to researches. Thermal analysis can be conducted experimentally or numerically. Experiment can be carried out on vehicle testing and in labouratory testing procedures. The present study used vehicle testing procedure for disc brake temperature variation.

Temperature monitoring is critical in almost every type of machinery and application, especially in rotating components such as brake disc, jet turbines, engines, power plants, etc. These components involve harsh environments and situations where the physical connections for monitoring systems are impossible. Temperature monitoring of rotating components could reduce the risk of component failure, ensuring equipment safety. However, acquiring temperature measurements of a rotating machine component using conventional methods can be costly and technically challenging [18]. This section presents an infrared (IR)-based wireless temperature measurement to monitor the temperature of rotating brake disc.

Huang and Chen's [19] load cycle was considered for temperature measurement. Huang and Chen's load cycle considered initial velocity of 27.78 m s^{-1} and decelerated at 0.45 g till the final speed of 0 m s^{-1}. Then accelerated from there on

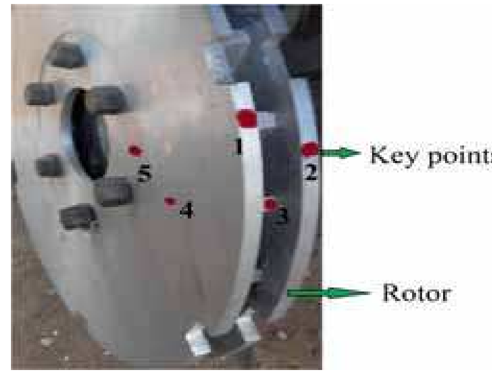

Figure 6. Key points marked in brake disc.

Figure 7. Temperature measurements at key points.

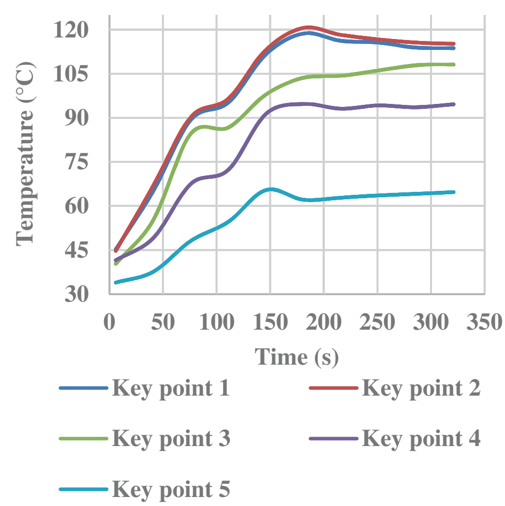

Figure 8. Temperature measured at key points.

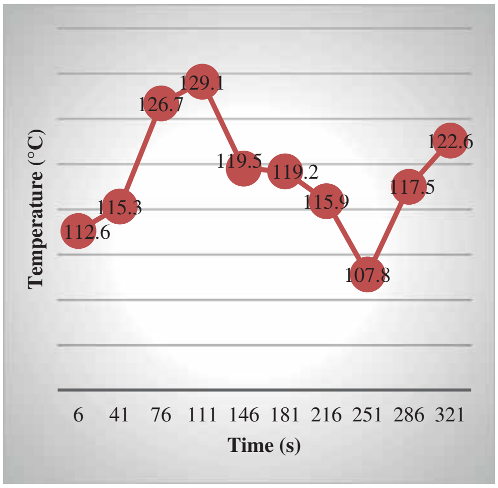

Figure 9. Maximum temperature measured at each cycle.

Table 2. Parameters in casting of brake disc.

Material	Value
Part defect rate (%)	2
Core defect rate (%)	2
Metal price (Rs)	1750
Material markup (%)	5
Production	
Mold-making labour (Rs h^{-1})	1200
Core-making labour (Rs h^{-1})	600
Cleaning labour (Rs h^{-1})	300
Plant efficiency (%)	90
Production markup (%)	5
Tooling	
Tooling material	Wood
Tool-making rate per hour	1

Table 3. Sand casting cost for brake disc based on quantity.

	Unit quantity	Monthly quantity	Quarter quantity	Annual quantity
Assembly quantity	1	9	25	100
Material cost (Rs)	1750	1750.00	1750	1750
Defect cost (Rs)	7000	777.78	280	70
Production cost (Rs)	2100	2100.00	2100	2100
Tooling cost (Rs)	7000	777.78	280	70
Total unit cost (Rs)	17,850	5405.60	4410	3990

till 27.78 m s^{-1} at 0.28 g and for remaining 25 s maintained a speed of 27.78 m s^{-1} (100 km h^{-1}). The vehicle was subsequently accelerated up to the same initial velocity and rotor was allowed to cool again before the cycle was repeated up to 10 times. Total time of ten load cycles was 350 s which consists of ten cycle of braking operations and ten cycles without braking operation (idle). As shown in figure 5, each cycle consumes 35 s split into 6 s of braking operations, 4 s for accelerations and another 25 s for maintaining constant speed.

Infrared technology though used successfully in industrial and research settings for decades has improved with new innovations having reduced costs, increased reliability, and resulted in noncontact infrared thermometer offering smaller units of measurement. This made infrared technology an area of interest for new applications and users.

Infrared thermometer measures the surface temperature of an object. The unit's optic senses emit, reflect, and transmit energy which is collected and focused onto a detector. The unit's electronics convert the information into temperature reading which is displayed on the unit. The laser pointer ensures ease and accuracy and aims for even more precise measurement. It is compact, rugged and easy to use. Just aiming and pushing the button, reads the current surface temperatures in less than a second. It safely measures surface temperatures of hot, hazardous or hard-to-reach objects without contact. Key components with possible hot spots were determined based on key points used in simulation results. The key points were marked at beginning of each experiment. There are five key points decided which is shown in figure 6.

The brake disc was fitted in a TATA Sumo vehicle. During operation, the disc was secured with a clamp and rotated at 3000 rpm. The heat shield was used to minimize the influence of surrounding heat sources or cold draft to the measured temperature. The IR head was placed 20 cm from rotating brake disc. In addition, it was ensured that the background did not have any hot spots which might be reflected off the plastic cover surface thus affecting the measurement. To determine the duration of each experiment, the disc was set to run at a controlled ambient temperature of 22 ± 0.1°C with same operating condition. Due to the relatively high angular speed, the flow was assumed to be turbulent everywhere over the disc. The brake was applied as per Huang load cycle. Temperatures were measured for each cycle by repeating the same experiments three times. For the repeated measurement of a cycle, the cycles were continued till the cycle which is interested to measure the temperature. For accurate and easy temperature measurement, the temperatures were measured immediately after completing braking action. The temperature measurements at key points are shown in figure 7.

5. Results and discusions of temperature measurement

The temperatures were measured at key points for each cycle. Figure 8 shows the results of temperature measured at key points.

The maximum temperature rise in each cycle is critical and it needs special attention. From key point temperature results, the maximum temperature raised at the limb of disc which was key point 2 compared to other key points. Figure 9 shows the temperature measured at key point 2 for braking of each cycle.

From figure 9, the maximum temperature generated along the brake disc rotor surface was 129.1°C. In the turbulent

Table 4. Machining cost for brake disc.

Work centre name	Operation notes/ description	Setup hours	Run time minutes	Net hourly rate (Rs)	Setup rate (Rs)	Setup cost (Rs)	Unit run cost (Rs)
2 Axis lathe	Grip ID: Finish face & OD	1.5	9.535	1528.20	1528.20	2292.60	243.00
2 Axis lathe	Grip OD: Finish face & ID	1.5	7.558	1528.20	1528.20	2292.60	192.60
3 Axis medium mill	Drill to Ø18.00 mm at 6 places	1	4.068	1528.20	1528.20	1528.20	103.80
Bench deburr		0	2.000	1063.20	1063.20	0.00	35.40
Total unit cost		4	23.161			6113.40	574.80

Table 5. Machining cost for brake disc based on quantity.

Cost in rupees	Unit quantity	Monthly quantity	Quarter quantity	Annual quantity
Assembly quantity	1	9	25	100
Setup	6113.40	679.20	244.80	61.20
Labour	574.20	574.20	574.20	574.20
Material	1750.00	1750.00	1750.00	1750.00
Scrap allocation	1750.00	462.00	332.40	208.20
Perishable tooling	0.00	0.00	0.00	0.00
Total unit cost	10187.60	3465.40	2901.40	2593.60

Table 6. Total cost for brake disc based on quantity.

Cost in rupees	Unit quantity	Monthly quantity	Quarter quantity	Annual quantity
Assembly quantity	1	9	25	100
Sand casting	16100.0	3655.60	2660.0	2240.0
Machining	8437.6	1715.40	1151.4	843.6
Material	1750.0	1750.00	1750.0	1750.0
Total unit	26287.6	7120.96	5561.4	4833.6

Table 7. Cost comparison between AA6063 and composite (for 100 quantities).

Cost in rupees	AA6063 (Rs)	Composite (Rs)
AA6063 material	1750.00	1527.50
Cenosphere	—	9.60
Magnesium	—	31.15
Sand casting	2240.00	2240.00
Stirrer step	—	50.00
Stirring labour	—	10.00
Machining	843.60	843.60
Total unit cost	4833.60	4711.85
Weight of unit disc (kg)	6.50	5.235

regime the fact that the adiabatic wall temperature rises towards the disc limb gives an increase of the heated disc surface temperature in that region [20,21].

6. Cost estimation of brake disc

A majority of manufactured goods and equipments contains cast parts making casting an important manufacturing process. Ascertainment of manufacturing cost varies among foundries due to unique combination of equipment, automation level, worker skill, and past experience they possess and the tooling (patterns, core boxes and moulds) and methodology (feeding and gating systems) adopted by them based on the knowledge gained from previous projects. The assumptions involved for casting cost estimation is listed in table 2.

Assumptions: 1. AA6063 price Rs. 250 per kg (table 3). 2. Machining stock considered 10 mm in OD & ID, 5 mm in faces (table 4). 3. Material weight calculated as 7 kg (table 3).

Total cost included casting cost and machining cost. Total cost based on quantity is shown in table 6.

Initial cost estimations for AA6063 material were made to manufacture brake disc. The main reason was that AA6063 was the standard material used and its manufacturing cost details were readily available. Following section describes the cost comparison between AA6063 and cenosphere-AA6063 composite (table 7).

The cost computed was 2.5% less than the pure AA6063. As the lifetime of the composite is longer, the lifecycle cost becomes half of that of AA6063 rotor. Apart from this the resultant weight reduction significantly influences the cost of other internal systems of the wheel positively. The weight reduction achieved in composite is 20% compared to AA6063 brake disc. Comparatively the conventional composite materials contain silicon carbide (SiC) or aluminium oxide (Al_2O_3) particles that are more expensive than the ceramic particles derived from flyash [1]. Generally the conventional composite increase the weight compared with base alloy.

7. Conclusions

In this study, manufacturability of brake disc was ensured by casting the brake disc with 10 vol% cenosphere. Machinability was ensured by adopting same machining process of base alloy. Thermal characteristics on brake disc by experimentation with vehicle testing procedure was successfully achieved. Cost estimation results of composite brake disc was compared with AA6063. Analysis of manufacturing cost showed that cost reduced by 2.5% as compared to AA6063. The cost reduction has to be correlated with weight reduction and life cycle cost. Also manufacturing cost of conventional composites are expensive than cenosphere composite. The weight reduction achieved is 20% less than the base alloy.

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