Inadequate wear resistance and low seizure loads prevent the direct use of aluminum alloys in automotive parts subject to intensive friction combined with high thermal and mechanical loading, such as brake discs, pistons, and cylinder liners. To enable the use of aluminum alloys in the production of automotive brake discs and other wear-resistant products, the insertion of a monolithic friction cladding rather than surface coating has been considered in this work. Three experimental approaches, two based on the pressureless infiltration of porous ceramic preforms and one based on the subsequent hot rolling of aluminum and metal-matrix composite strips, are currently under investigation.

**INTRODUCTION**

Over the last decade, automotive industry representatives identified automobile weight reduction as an effective way of improving their product competitiveness as well as their ability to make profits (apparently through improved fuel efficiency, exhaust emission reduction, enhanced safety, and vehicle driving performance). Perhaps, as a result, aluminum use in passenger cars is increasing steadily.1

The chassis, which accounts for about 27% of the weight of the entire average car, is under serious consideration for additional weight reduction. Particular attention is to be paid to reducing the weight of brake components,2 which are currently fairly heavy. However, the improved fuel efficiency and consequent lower exhaust emissions are not the only benefits of weight reduction. Lightweight aluminum-based rotors also provide increased acceleration, reduced braking distance, reduced noise (groan and squeal), higher wear resistance, and uniform friction.

Attempts to replace cast iron in disc brake rotors, drums, and calipers with aluminum-based materials have been ongoing since the mid-1980s.

**BRAKE ROTORS**

As with most soft metals, aluminum suffers from poor resistance to adhesive wear or galling when in relative motion with another metallic or non-metallic surface. Several solutions to this problem have been proposed, including high silicon and beryllium-aluminum alloys and various composites.3,4

Two main design concepts have been applied: a homogeneous brake rotor and a brake rotor consisting of a core lined with friction cladding.

Although brake rotors made from high silicon and beryllium-aluminum alloys may reach minimal friction and wear performance standards, they still cannot achieve the performance level of the traditional cast gray iron brake rotor. The main problems are poor wear resistance and a low coefficient of friction.

To improve the wear resistance and to increase the coefficient of friction, aluminum metal-matrix composites (MMCs) reinforced with 20–35 vol.% of ceramic particulate were proposed.5 Because of their superior friction and wear properties, as well as the considerable alteration in mechanical behavior (tensile, yield, fatigue, creep, and impact strengths) and physical properties (thermal expansion and thermal diffusivity) that the addition of ceramic particulate provides to the base alloy, these materials are capable of functionally replacing cast iron and cast gray iron in automotive brake components. However, due to the high cost of composite materials relative to non-reinforced aluminum alloys, as well as costly brake rotor forming and machining procedures, current aluminum MMC brake rotors cannot be cost-competitive with cast-iron equivalents.

Monolithic ceramic materials are also an interesting alternative in replacing cast and gray cast iron in brake rotors. Ceramic brake rotors are already available for racing and luxury cars.6 The discs are produced in two halves from a blend of carbon fibers and liquid polymers thermally compressed in a mold. Once hardened, the rough discs are carbonized by pyrolysis (in a furnace with a nitrogen atmosphere) at temperatures approaching 1,000°C. In this way, all polymers not made of pure carbon are converted into carbon. After that, the discs are “siliconized” at 1,800°C in a 20 kPa vacuum. In spite of a 25% improvement in friction coefficient over gray cast-iron discs, a 50% weight reduction, and a lifetime equal to the lifetime of the car, the monolithic ceramic brake disc is too expensive to be used in passenger vehicles.

As it became more apparent that homogeneous composite and ceramic materials cannot provide a cost-effective lightening of the automobile brake disc, nor impart all the necessary properties, a brake disc consisting of a core and friction cladding was introduced.7 To provide maximum weight reduction and optimal economy, the core material was selected to be a traditional non-reinforced aluminum alloy. On the other hand, advanced multifunctional materials that impart unique wear, friction, and thermal properties and effective bonding with the core were proposed for the cladding.

Two manufacturing directions for brake disc cladding were investigated:
insertion casting and surface-coating technologies. In both cases, the basic idea is the same—to process the cladding separately, using the most efficient and cost-effective technique. This approach allows engineering of the required properties locally—into particular functional zones of the cladding.

Various thermal and cold-spraying techniques are particularly effective in the production of such multi-zone cladding. Due to their inherent simplicity, these methods are cost-effective in scale-up manufacturing and also provide near-net shape processing capabilities. A coated brake disc technology that optimizes the aluminum brake disc and also makes the disc compatible with current brake pad technology is already in use.

Apart from the many benefits of the spray technique, the cladding obtained in this way has only a limited thickness of the friction zone (maximum 1–2 mm), which significantly reduces the lifetime of the component. In addition, the deleterious effects of high-temperature oxidation, evaporation, melting, crystallization, residual stresses, de-bonding, gas release, and other common problems of spray methods reduce the lifetime of such cladding.

In order to prolong the lifetime of the frictional zone of the cladding, other producers are practicing insertion casting. There are several modalities and commercial names for this method reported in the literature, depending on the porosity level in the applied ceramic preform and the reactivity between the preform and molten aluminum alloy.

Basically, a porous or dense ceramic preform is fed into the cavity of the mold. The molten metal for core preparation is then poured into the mold, adhering to the preform in the mold. In the case of a dense ceramic insert, adherence is achieved by reactive penetration. In the case of a porous insert, bonding is caused by infiltration.

Until now, insertion casting has been mainly practiced for the local reinforcement of aluminum-alloy substrates with ceramic particulate. Although surface reinforcement of an aluminum-alloy brake rotor with ceramic particulate increases the friction coefficient and improves wear resistance, other problems remain, in particular, thermal degradation of the discontinuously reinforced composite, as will be discussed later. In some cases, the lack of a solid lubricant such as graphite represents another serious problem. The lack of graphite in the system results in low braking efficiency, adhesive wear, and galling. In the traditional cast-iron rotor, graphite is always present in the iron. As the brake wears, the graphite is freed from the iron matrix to be utilized as a solid lubricant on the wear surface. To overcome this problem, nickel-coated graphite particles have been incorporated into aluminum-silicon-carbide composite cladding by a patented insertion casting procedure named the CastCon process. Prototype brake rotors were developed and reported as having better wear resistance than a cast-iron rotor. However, the temperature that the rotor reached during tests with the same braking input as a cast-iron rotor exceeded the maximum operating temperature for the composite material. This demonstrates that a single-layered cladding could not meet all the necessary multi-functional requirements, which may be completely addressed by multi-layered cladding structures.

To achieve the optimal balance of properties at the friction surface and inside the multi-layered cladding, the composition and thickness of each brake disc temperature management

During braking, through friction in the brakes, the kinetic and potential energy of the moving vehicle are converted into thermal energy distributed between the rotor and pad. The percentage of the total braking energy absorbed by the rotor, which can be expressed in terms of material properties, is about 70% for a medium-size passenger car. Consider a midsize passenger car with a mass of about 2,000 kg, decelerating at 0.8 m/s² from a speed of 128 km/h without brake lock-up. For this case, one can calculate that the average braking power absorbed by one half or one side of one front brake would be about 20 kW. Hence, the heat-flux into the friction area of the brake rotor with a friction area of 300 cm² would exceed 600 kW/m².

In the standard SAE D-212 friction test for vehicles sold in North America consisting of 15 stops from 96 km/h with a deceleration rate of 0.5 m/s² and 35 s intervals between braking, the temperature measured on the friction surface of gray cast-iron brake rotor increased to 484°C. Under the same test conditions, the temperature measured on the friction surface of an aluminum MMC rotor (alloy A356 reinforced with 20 vol.% of SiC particles) was even higher (542°C). The surface temperature of a ceramic (SiSiC) brake disc exceeded 800°C.

Even if the rotor and pad are made from high-temperature wear-resistant materials, the high temperatures on the friction surfaces adversely affect their wear rate and lifetime. To protect both rotor and pad, an operating temperature of <370°C is recommended. To remain below 370°C, brake rotor designers tried to intensify the convective heat transfer from friction surface to air by introducing air-cooling channels and cross-drilled holes. However, apart from some limited success in lowering the friction surface temperature, air cooling tends to be ineffective because the disc fits inside the wheel well. It is particularly ineffective in the case of the ceramic brake disc, where six-pot front calipers and four-pot rear calipers are standard units, apart from a ceramic heat shield on each piston to prevent heat flow from the high disc temperatures boiling the brake fluid.

The most effective way of managing the friction surface temperature is by tailoring the thermal conductivity of the friction layer. One approach is based on applying a high-temperature wear-resistant friction layer with a low thermal conductivity and a high-temperature wear-resistant pad material with a high thermal conductivity. The low thermal conductivity of the friction layer minimizes heat flow from the cladding to the core region and favors the accumulation of heat into the friction zone of the rotor. Hence, the temperature at the friction surface increases rapidly and a strong temperature gradient through the friction layer is generated. However, at the same time, the high temperature at the friction surface significantly promotes convective heat transfer from the rotor to air. In this respect, an equilibrium temperature, T_eq, at the friction surface between 370°C and 600°C would be managed to promote competitive lifetimes of both pad and rotor.

The opposite approach is based on applying a high-temperature wear-resistant friction layer with a high thermal conductivity. Due to its high thermal conductivity, most of the heat absorbed by the friction layer will be conducted toward the core or the air-cooled channels. As a result, the temperature at the friction surface will be kept below 370°C.