B. Low-Cost Cast Aluminum Metal Matrix Composites

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Objective

- Provide lightweight, cost-competitive, aluminum metal-matrix composite (MMC) options for future vehicles and hybrid structures, with a project application focusing on foundation brake system components. This project focused on three development tasks, which include (1) development of compositing technologies to produce low-cost MMC materials; (2) advanced shape-casting manufacturing processes; and (3) innovative designs for new brake rotor applications.

Approach

- Develop advanced MMC processing technologies and integrate these processes into an economical manufacturing cycle, including consideration of product design that accounts for material-specific characteristics and component performance. The specific major project tasks follow:
  - Develop rapid MMC mixing process and lower cost, castable aluminum MMC material
  - Evaluate mechanical and physical properties, as well as castability of this material
  - Friction and wear test sample products produced from the low-cost MMC material
  - Explore innovative casting and finishing options
  - Provide innovative brake system designs to utilize aluminum MMC materials
  - Prototype and full-scale test demonstration components (brake rotor)

Accomplishments

- Completed material property and foundry evaluation.
- Completed and validated cost modeling at pilot scale.
- Completed and prototyped evaluation of squeeze casting of fully reinforced rotor, and completed brake dynamometer testing.
- Completed centrifugal casting of selectively reinforced rotor prototypes and initiated dyno testing.
- Completed machining cost and tool life study.

Future Direction

- Complete economic evaluation of centrifugal casting for large volume production of aluminum components.
- Complete dynamometer testing of prototype, selectively-reinforced, aluminum MMC brake rotors.
- Pacific Northwest National Laboratory (PNNL) will investigate the use of centrifugal casting to demonstrate the production of a selectively-reinforced brake rotor caliper with the reinforcement located in the bridge region of the caliper.
- Draft final program report.

Introduction

The demand for better fuel economy is a major reason to reduce vehicle mass. In principle, the substitution of aluminum metal-matrix composite (MMC) material for steel components provides a significant opportunity to reduce vehicle mass in a number of automotive applications. Aluminum MMCs possess both light weight and high wear-resistance characteristics, making them desirable for a number of body, chassis, and powertrain applications, provided that performance and cost objectives can be reached. A brake rotor was selected as a demonstration piece for this project to show that the low-cost material developed in the initial phase of this project is viable for use in a challenging application that has potential for substantial mass savings.

While a number of niche automotive applications of aluminum MMCs have been made—including the Toyota diesel engine piston, Honda Prelude cylinder liner, General Motors (GM) S/T drive shaft, and rear brake rotors on the Plymouth Prowler, Lotus Elise, and Volkswagen (VW) Lupo—they have not seen widespread automotive application due primarily to cost and, in some cases, performance limitations. It was the purpose of this project to make a significant improvement in this situation.

With the overall goal of demonstrating cost-competitive aluminum MMC options for structural and powertrain components in general, the project focused its attention on a lightweight brake rotor as a target application. In cooperation with Visteon Corporation, a lightweight rotor that is 60% lighter than a conventional four-door luxury sedan cast iron rotor was designed and manufactured. Since the rotor is rotating, unsprung mass, the opportunity for improved fuel economy due to this substitution has been estimated to be on the order of 0.25 mpg from not only the direct weight reduction but also the resulting lower inertial forces. The cost of the prototype rotor is estimated to be 1.5 times the cost of a cast iron rotor, compared to a figure of three times or so for prior aluminum MMC rotors.

This project began with the development of a low-cost aluminum MMC material and process for making it. This venture was an industry-government collaboration between MC-21, Inc., U.S. Council for Automotive Research (USCAR), Pacific Northwest National Laboratory (PNNL), and the FreedomCAR Automotive Lightweighting Materials Program. While prior aluminum MMCs sold for prices of \$2/lb or more, a more economical rapid mixing process for combining the aluminum and silicon carbide ceramic particles was developed. This process utilizes a modular mixing unit and lower cost raw materials, resulting in a projected material cost of \$1/lb, which is more than a 50% savings. This process has been demonstrated at a 600-kg batch size level, which is suitable for production of 5 million pounds of aluminum MMC per year from one unit. Commercialization is under way with multiple licensing agreements complete or in negotiation.

The thermal and structural properties of new low-cost MMC materials have now been evaluated and found to be acceptable. Also, the cost model for the low-cost MMC material showing that \$1/lb is feasible at pilot-scale volumes was validated by commercial entities. To demonstrate the material's potential, prototype full-scale, fully-reinforced brake rotors were produced by a squeeze-casting method. This method was selected as being the most economical of the several innovative shape-casting methods that were evaluated.

Computer simulations and brake dynamometer tests show that it is possible to achieve acceptable performance for either front or rear brakes of a mid-size sedan using the new low-cost aluminum MMCs. The novel brake rotor design enhances dissipation of the heat generated during braking and prevents excessive temperature increase. Prototype castings of full-scale brake rotors based on the design and simulation results were produced and dyno tested by Link Engineering. A spider-chart representing the status of the major project tasks is shown in Figure 1.

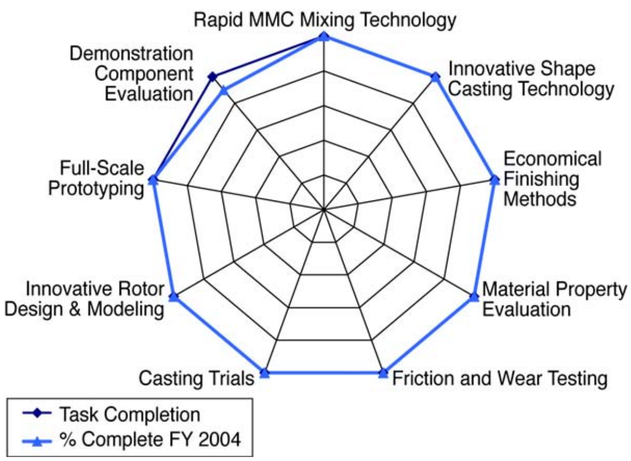

Figure 1. Status of project tasks and completeness.

Brake Rotor Prototyping and Dynamometer Testing

Having a low-cost material is a necessity, but it is not totally a sufficient condition to realize low-cost automotive products. With the success of the low-cost material development, the project team next addressed the secondary manufacturing cost issues. This also included identifying an innovative design for a brake rotor that would take into account the unique properties of MMC vs cast iron, such as higher thermal conductivity and lower maximum operating temperature capability. The patented externally vented rotor design shown in Figure 2, which was developed by Visteon, achieves the necessary thermal performance criteria based on brake dynamometer testing. Also shown in Figure 2 is the standard cast iron front disc brake rotor for the target four-door sedan as well as details on the physical differences and weight savings between the two. The rotor performance meets the braking requirements for a midsize sedan, with some future

Production rotor – four-door sedan	Aluminum MMC rotor (designed for same four-door sedan)
• 300-mm diameter by 30 mm wide	• 300-mm diameter by 32 mm wide
• Gray cast iron — green sand cast	• Aluminum with 20% silicon carbide — die cast or subliquidus cast (semisolid formed)
• Internally vented — 7.0-mm outer plate / 15.0-mm air gap / 8.0-mm inner plate	• Externally vented — alternating inboard (20) vents and outboard (20) external vents
• 6 Short and long alternating vanes	• Internal heat sink venting in hat section to better distribute heat
• Weight = 8.44 kg	• Weight = 3.32 kg

Figure 2. Comparison of production sedan rotor (left) and specially designed prototype lightweight aluminum-MMC front brake rotor (right).

work still needed on friction materials to optimize noise and pad life.

Working with team members THT Presses and Eck Industries, the externally vented rotor design was adapted for squeeze casting. Through this high integrity process, a number of features, including the mounting holes, can be produced in the casting process, which helps to minimize the need for extensive final machining. Current work with team member Kennametal is finalizing cutting tool materials and process parameters for production-scale machining of the rotors, recognizing the interrupted cut condition presented by the externally vented design.

Prototype brake rotors were produced for full-scale dynamometer evaluation of braking performance and durability. The tests were conducted by Link Engineering with the appropriate load and speed parameters that simulate front disc brake operation on a midsized four-door sedan, weighing approximately 3,700 lbs. The brake pad lining selected for testing is a commercially available formulation from Akebono that is used on other aluminum MMC brake rotors where the maximum operating temperature (MOT) is low, and application is for a rear brake only.

Of the six types of test profiles run for the evaluation, five of the six tests met the minimum performance requirements established and were given a passing grade, which is summarized in Table 1. The brake noise test was marginal in the evaluation with a final rating of 7 (Yellow), which is an industry index that designates an average noise level at the threshold for acceptability. The type of lining used for braking systems can have a significant effect on the amount of noise generated. Visteon feels this issue is correctable with different pad formulations, slight rotor geometry changes, or a combination of both.

Table 1. Results of initial prototype brake dynamometer testing

Test description	Pass/fail
Dyno simulation of AMS and fade test	Pass
Dyno simulation of Laurel Mountain hot roughness brake test	Pass
Brake lining wear vs temperature test	Pass
Brake noise test (with steady drag)	Marginal
Disc wear test (with low-pressure drag)	Pass
Brake effective test	Pass

Of more concern was the friction coefficient results during the fade and drag tests. The concluding remarks were that the high-temperature friction under extreme conditions was marginal. Although the rotor integrity was not compromised at the higher surface operating conditions (since the structural properties and microstructure were retained), the coefficient of friction was relatively low at an average of 0.25. The current desired target within the industry for automotive disc brakes is a friction coefficient between 0.35 and 0.45, with values in the 0.40+ range being comparable to a “European luxury vehicle brake pedal feel.” This pad formulation is indeed acceptable for lower MOT, but it was not necessarily designed to perform at the higher operating condition of the smaller rotor geometry. The Visteon rotor cannot be made larger to compensate for mass and surface area because the smaller conventional passenger vehicle wheel sizes limit the maximum rotor diameter that can be utilized.

Although the overall performance of the new aluminum MMC brake rotor exceeded expectations for the first round of testing, it is necessity to improve the friction coefficient in order for it to be considered for production vehicles. To that end, a review of brake pad manufacturers was made, and a pad formulation from TMD was identified for testing. According to TMD, this pad formulation (composition not disclosed) is designed to operate with braking surfaces (rotors) such as aluminum where the development and integrity of the friction film is more difficult to develop and needs to be more stable at elevated temperatures.

A second series of brake dynamometer tests was conducted at Link Engineering to evaluate braking performance with the TMD linings. The coefficient of friction during all of the tests was much higher than the first series with the Akebono linings, with values as high as 0.45. The average friction coefficient for this series of tests was within a desirable range, with values of 0.38–0.40. The same improved results also applied to the effectiveness curves and the rotor-speed-spread, pressure-spread, and temperature-spread data. In other words, this specific rotor and lining combination held up better under the higher temperature friction conditions.

The summary of results for the second series of testing is given in Table 2. Like previous test results,

Table 2. Results of brake dynamometer testing with TMD linings

Test description	Pass/fail
Dyno simulation of AMS and fade test	Pass
Dyno simulation of Laurel Mountain hot roughness brake test	Pass
Brake lining wear vs temperature test	Fail
Brake noise test (with steady drag)	Pass
Disc wear test (with low pressure drag)	Pass
Brake effective test	Pass

noise was an issue with a noise index rating of 5 (Red). Although the braking performance was significantly improved with the somewhat harder TMD lining, unfortunately the trade-off was more noise, which is a typical struggle for brake system designers. Visteon is confident that the level of noise and frequency is correctable with slight modifications to the rotor geometry, which should have little impact on thermal management and braking performance.

Machining Evaluation and Tool Life Study

The objective of this study was to determine tool material performance and machining parameters for turning aluminum (20 vol % SiC) MMC of representative brake rotor geometries. Diamond is clearly the tool material of choice for machining most MMCs; however, it was not clear whether diamond cutting edges could reliably withstand the very severe interruptions in the design of these rotors. An initial review of commercial and emerging tool materials determined that two types of diamond tool material commercially available from Kennametal, Grades KD100 and KD1405, would be pursued. KD100 is a 25-µm diamond-particle-size grade produced by the classic high-temperature/high-pressure process, which is a composite material consisting of bonded diamond particles and a small amount of cobalt catalyst. Polycrystalline diamond (PCD) tools of this type were among the first recommended for economically machining aluminum MMC materials. KD1405 is an essentially pure PCD tool fabricated by using chemically-vapor-deposited (CVD) diamond sheet material, ~400-µm-thick blanks at the cutting edge. In machining very abrasive, nonferrous workpiece materials, such as A390 (~18% silicon) aluminum, KD1405 typically exhibits two to three times the tool life of KD100 and provides superior workpiece finishes. However, KD100 typically shows better toughness in interrupted cutting applications.

Turning parameters for this study ranged from cutting speeds of 900–2000 surface feet per minute (sfm), feed rates from 0.005–0.020 inches per rotation (ipr), and depths-of-cut (DOC) of 0.020 in., thus providing material removal rates ranging from 1.08 to 9.6 in.^{3}/min. A total of 22 rotors with discontinuities in the cutting surface and two rotors with solid faces were supplied for the experiments, with the later rotors for use in evaluating tool wear under continuous cutting conditions. The setup used to machine the rotors included a Okuma LR35 lathe and KM50-CSKPL4 tool-holder, which imparts a +15° lead angle and a +5° rake angle to the diamond cutting edge. For each pass, cutting was initiated from the outside diameter of the rotor to the inside, while automatically adjusting the spindle revolutions per minute to maintain constant cutting speed. Flood coolant, Castrol–Syntilo 9904 at 5 vol %, was used throughout each test.

The first cut on each rotor was a clean-up pass of 0.020-in. DOC to remove surface nonuniformities and present a fresh surface to the cutting edge of the test insert. It was decided to use one test insert for each rotor, at a DOC of 0.020 in., which meant that the insert could be used for a maximum of 22 passes. Measurements of maximum nose wear and uniform flank wear were made after each of the first two passes and then after every other pass thereafter. Workpiece surface finish (µin.) measurements were made after each pass using a hand-held profilometer. The normal end-of-life (EOL) criteria for testing PCD tools in laboratory tests is 0.015-in. maximum nose wear, chipping, or cutting-edge breakage, whichever occurs first. However, because premature chipping or breakage was not observed in this test, there were insufficient rotors available to allow running each insert to EOL. Accordingly, linear regression analyses of the wear data were performed to calculate wear rates (µin./pass or µin./min) and an estimate of tool life for each insert at 0.015-in. maximum flank wear.

Results showed that there was no significant difference in tool performance between KD100 and KD1405 at the low-speed/low-feed and at the high-speed/high-feed cutting conditions studied. However, at low-speed/high-feed and high-speed/low-feed conditions, the KD1405 showed a significant tool life advantage of >4X, and greater cost effectiveness at 900 sfm/0.020 ipr. As expected, smoother workpiece finishes (65 vs 350 µin. radius) were produced at the lower feed rate, but there was no significant difference in the finishes produced by the two types of tools. Typical wear characteristics in the cutting zone of the tools after interrupted cutting at 2000 sfm/0.005 ipr are shown in Figure 3 for KD100 and KD1405. Both tools showed abrasive wear patterns, but with no evidence of chipping. Mildly abraded regions are clearly evident in the chip-flow zone on the rake surface of the tools. Maximum wear occurred at the leading edge of the tool where it enters the cut, with generally uniform wear observed around the nose of the tool. Of the tools tested, only one, a two-nose radius KD1405 insert, chipped and fractured catastrophically on making an initial pass through the vented rotor. All others showed wear patterns similar to those illustrated in Figure 3.

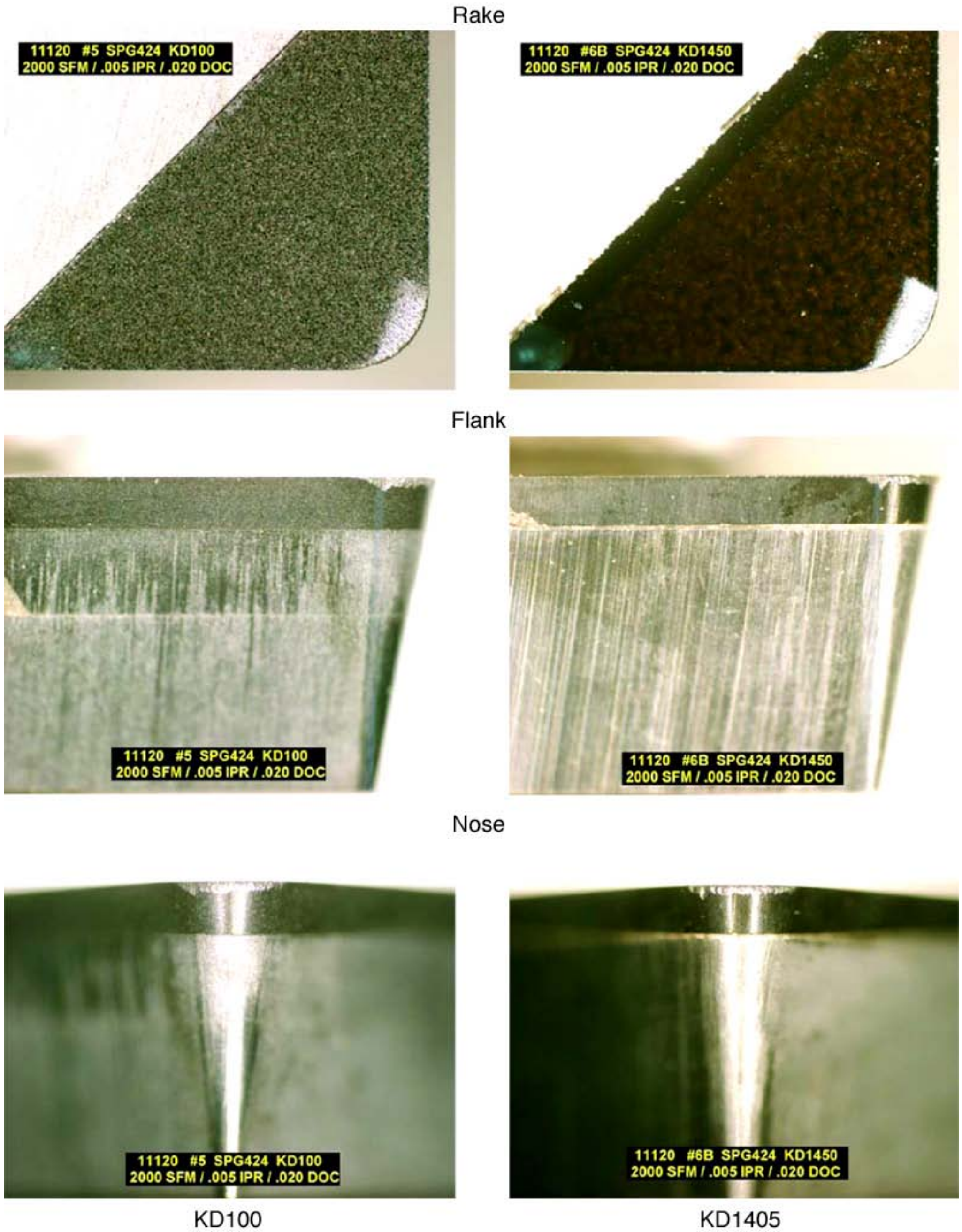

Figure 3. Wear zone of inserts after interrupted cutting at 2000 sfm/0.005 ipr.

On the basis of the estimated tool life data and the material removal rates corresponding to the machining parameters, the amount of workpiece material removed by KD100 totaled 824 $in.^3$ and that for KD1405 amounted to 1353 $in.^3$ At insert costs of $55 for KD100 and $105 for KD1405, the corresponding cutting edge costs under the test conditions are $0.067 vs $0.078/$in.^3$ machined, respectively, giving a slight economic benefit to KD100.

Tool nose radius had an effect on tool life. Performance data for SPG422 and SPG424 inserts in grade KD1405 showed that the four-nose radius (0.0625-in.) tools had about 60% less tool life than the two-nose radius (0.0323-in.) tools. It is possible that higher tool pressures for the four-nose radius tools could account for the higher wear rates and decreased tool life.

In summary, PCD and CVD-diamond sheet tool materials (KD100, KD1405) were tested in facing operations of aluminum-MMCs, with discontinuous cuts in the brake rotor braking surfaces. Although both tool materials performed well over a wide range of cutting parameters, KD100 inserts in style SPG422 provided the most cost-effective performance. The greatest tool life is expected by using a proposed roughing pass at 2000 sfm, 0.020 ipr, and 0.015 DOC, followed by a finishing pass at 2000 sfm, 0.005 ipr, and 0.005 DOC.

Future Work

The remaining scope of work will focus on completing the economic analysis of commercial centrifugal casting and prototyping and dynamometer testing of selectively reinforced aluminum-MMC disk brake rotors. In addition, PNNL will investigate the use of centrifuge casting to demonstrate the production of a selectively reinforced brake rotor caliper with the reinforcement located in the bridge region of the caliper.

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Presentations and Publications

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2. W. H. Hunt and D. R. Herling, "Applications of Aluminum Metal Matrix Composites: Past, Present, and Future," International Symposium of Aluminum Applications: Thrusts and Challenges, Present and Future, ASM International, Pittsburgh, Pennsylvania, October 2003.
3. W. H. Hunt and D. R. Herling, "Metal Matrix Composites," *Advanced Materials & Processes*, **162**(2), 39–42 (2004).
4. E. Oles, S. Etling, and J. Vankirk, *Machining Aluminum MMC Brake Rotors*, Project Report No. 14245, Kennametal, November 2004.
5. D. R. Herling, "Low-Cost Cast Aluminum Metal Matrix Composites Have Arrived," invited presentation at the 2003 TMS Materials Science & Technology Conference, Chicago, Illinois, November 2003.
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