Low-cost aluminum

METAL MATRIX COMPOSITES

The economics of the MC-21 rapid mixing process and lower-cost raw materials show a strong potential for being able to produce a castable 359/SiC/20p aluminum MMC product for close to $2.20 per kg ($1 per pound).

Darrell R. Herling*
Glenn J. Grant*
Pacific Northwest National Laboratory
Richland, Washington

Warren Hunt, Jr.**
Aluminum Consultants Group
Murrysville, Pennsylvania

Aluminum metal matrix composites (MMC) are appealing because of their low density and high specific stiffness. In addition, the ceramic-particle reinforcement significantly increases wear resistance. Nevertheless, high cost relative to conventional aluminum alloys has prevented widespread industrial applications.

Two primary factors account for the high cost of metal matrix composites. The first factor is the raw material cost of both the aluminum matrix material and the ceramic reinforcement particles. The second factor leading to higher cost is related to the fabrication process. If these two factors could be controlled and reduced, then a wider range of applications becomes possible.

Toward this end, Metal Matrix Composites for the 21st Century (MC-21) Inc., in Carson City, Nevada, has developed a novel process in which the particulate is rapidly mixed into the matrix alloy. The process significantly reduces the time required for mixing, and therefore can reduce the labor and ultimately the cost. In addition, the mixing system may be placed at a foundry, and the molten material may be transferred directly to the casting floor without the need for remelting of ingot. Furthermore, the selection of a lower-cost material for the reinforcement, rather than the expensive F-500 grade, would also reduce expense.

This article describes current MMC mixing processes, then discusses the MC-21 process, providing details of its operation and showing how it can reduce costs.

Conventional processes

Over the years, a number of compositing and mixing processes have been investigated and utilized for the production of aluminum MMC. These include both liquid and non-liquid techniques, such as mechanical mixing of reinforcement into molten metal, and powder metallurgy approaches. Powder metallurgy involves blending metal and ceramic powders that are compacted together and then sintered to create a solid, dense form. This method has proven expensive due to the high cost of metal powders and the associated production equipment, as well as time-consuming processing steps. However, powder metallurgy methods do have the benefit of being able to produce unique MMC material chemistries, with very fine particle reinforcement size distributions that otherwise are not possible with most molten metal techniques.

Stir-casting techniques are currently the most...
common commercial method. This approach involves mechanical mixing of the reinforcement particulate into a molten metal bath. A simplified compositing apparatus is shown in Fig. 1, and typically is comprised of a heated crucible containing molten aluminum metal, with a motor that drives a paddle, or mixing impeller, that is submerged into the melt. The reinforcement is poured into the crucible above the melt surface and at a controlled rate, to ensure a smooth and continuous feed.

As the impeller rotates at moderate speeds, it generates a vortex that draws the reinforcement particles into the melt from the surface. The impeller is designed to create a high level of shear, which helps strip adsorbed gases from the surface of the particles. The high shear also engulfs the particles in molten aluminum, which promotes wetting. Proper mixing techniques and optimized impeller design are required to produce adequate melt circulation and homogeneous distribution of the reinforcement.

Early stir-casting processes maintained a melt temperature between the solidus and liquidus temperatures. The higher viscosity of the semi-solid melt produced a higher degree of shearing during the mixing step, and this assisted in particle wetting. However, this technique, known as compocasting, has technical issues and limitations. Materials are typically compocast under atmospheric pressure, with ambient air or an inert cover gas above the melt surface.

Unfortunately, the same beneficial vortex that draws the reinforcement into the melt and produces adequate melt shearing, also draws in gas and oxide films from the surface. These contaminants are detrimental to the quality of the MMC and limit the rate of particle wetting and mixing. Other limitations of these early compositing processes included small batch sizes and a high level of porosity. These methods were ultimately rejected because they were not commercially viable on a large manufacturing scale.

Stir-casting technology developed little after the invention of the compocasting process, until it was merged with vacuum technology. Duralcan, a division of Alcan Ltd., is currently the leader in stir-cast aluminum MMC production and sales worldwide. The technology development that led to the Duralcan compocasting process incorporated the basic concept of the compocasting method into a vacuum environment, in which the uptake of gas in the melt could be avoided. In addition, mixing in a vacuum environment eliminated the gas boundary layer at the melt surface and eased the conditions for particle entry into the melt from the surface.

An improvement in mixing efficiency and compositing temperatures above the liquidus point resulted in the production of a superior aluminum MMC. Alcan currently produces castable aluminum MMC in 6800 kg (15,000 lb) batch sizes, with good quality and a range of silicon carbide (SiC) particle reinforcement levels from 10 to 30 vol%. After stir-casting, the aluminum-SiC composite is cast into 14 kg (30 lb) ingots that are sold to foundries for remelting and casting.

Currently, the cost for Duralcan F3S.20S MMC product, which is a stir-cast 359/SiC/20p castable aluminum MMC material, is approximately $5.50 to $6.60 per kg, depending on the quantity of material purchased. The relatively high cost compared with high-silicon aluminum alloys or high-strength lightweight steel, is a direct contributor to its limited application in many markets. In cost-sensitive industries such as automotive, the availability of a lower cost, castable aluminum MMC material would enable widespread application to many powertrain components, such as brake rotors or suspension arms. To address this need, MC-21, in conjunction with researchers at the Pacific Northwest National Laboratory, has developed an evolutionary rapid mixing and compositing process for the production of low-cost aluminum MMC materials for casting applications.

The rapid mixing process

The MC-21 MMC rapid mixing concept, as described by U.S. Patent No. 6,106,588, avoids many of the technical issues associated with the Duralcan process by mixing the aluminum and reinforcement materials at or near atmospheric conditions. Ambient air eliminates the need for the complex and expensive vacuum system, and potentially lowers capital equipment costs. A controlled inert atmosphere, such as argon or nitrogen, can prevent the melt from reacting with the oxygen in the air, effectively reducing the build-up of an oxide layer.

The mixing head is similar to that for other stir-casting methods, in that its primary purpose is to break up particulate agglomerations, create a high level of shear forces in the melt, and effectively mix and distribute the reinforcement. However, unlike other stir-casting mixing head designs, the specific design does not produce a vortex when rotated in the melt. In addition, baffles at the top of the melt help eliminate significant surface movement and prevent pulling oxides from the surface into the melt.
The novel approach of this concept is based on how the particulate reinforcement is introduced to the melt. The powder is metered into the melt through a hollow mixing shaft, and is introduced into the melt below the surface, as shown in Fig. 2. The mixing head is designed to promote the breakup of particle agglomerations and to effectively distribute the reinforcement in a vertical rolling motion. Higher shear forces are achieved by processing in a semi-solid state, where the viscosity of the melt is higher.

Since the impeller design does not create a vortex in the melt, the rotating speed can be significantly increased, which tends to further enhance the size of the shear region and particle wetting efficiency. In the rapid-mixing process, the higher level of shear and the larger shear region that builds in the melt improve the mixing action of the particles. In addition, the position of the shear zone is at an optimum location, where the particles are first introduced into the matrix material as they diseminate from the hollow mixing shaft. This reduces the time required for the particles to reach the shear region, and significantly increases the fraction of particles that pass through the shear zone. This leads to an increase in the rate of wetting.

The addition of a stationary impeller base underneath the impeller head can further boost the shearing action, if it is placed in close proximity to the outlet of the hollow mixing shaft and has a profile complementary to that of the impeller. Fluting or contouring the top of the mixing base can tailor the specific shear characteristics. This modifies the mixing action in the shear zone and helps control the compositing process.

Through mixing trials, MC-21 has shown that this rapid mixing technique significantly reduces the time required to stir-cast aluminum MMC materials by at least 80%. The reduced compositing time ultimately influences the labor costs. Manufacturing cost estimates for the MC-21 rapid mixing process indicate that the process should enable economical compositing of aluminum MMC for approximately $0.33 per kg.

Additional cost reduction

The key to the MC-21 rapid mixing process is the ability to quickly and efficiently incorporate the reinforcement particles into the matrix material, and allow for more versatile mixing conditions. However, other aspects of the process besides the mechanical mixing can make it more efficient. For example, more efficient equipment and process designs can be applied to provide an overall systems approach that is less labor-intensive. To further promote casting efficiency of MMC components and reduce labor time, the MC-21 compositing system is designed in a modular form that can be placed on the foundry floor.

The system consists of three primary units, a melter, a mixer, and a holding furnace. The melting unit melts the matrix alloy ingot prior to mixing, via either resistive heating methods or a reveratory heating unit. After the matrix alloy is melted, the molten material is transferred into the mixing unit, where the particulate reinforcement is added in a controlled manner through a proprietary powder injection system, and is then mixed into the matrix material. After the compositing step, the MMC material is transferred to the holding furnace. The furnace has a low-speed mixing head, producing a gentle agitation that keeps the particulate from settling out.

This modular approach provides several benefits for the production of aluminum MMC materials. Because it is transferred to a holding furnace after the mixing step, the mixer is then immediately free to produce another batch. The process steps are sequenced so that production is semi-continuous, which can effectively increase the overall output quantity during every shift. In addition, by transferring the material to a holding furnace in a liquid state, it is subsequently poured or ladled directly into the casting molds without the need for remelting. Elimination of the remelting step can increase productivity by eliminating the time necessary to melt the MMC ingot prior to casting. In addition, part-manufacturing costs can be reduced since the labor, furnace energy, and other expense associated with remelting and shipping of MMC ingot are removed.

Because the system is modular, each unit can be scaled according to foundry casting needs, and may supply MMC material only when necessary. This helps to reduce inventory and overhead costs. A prototype rapid mixing unit, shown in Fig. 3, was built by MC-21, and is capable of producing 600 kg (1320 lb) of aluminum MMC per cycle. The moderate size and flexibility of the compositing process allows for quick changeover to different MMC products (different matrix alloy and reinforcement combinations), and provides for more versatility, especially for smaller foundries that specialize in casting unique MMC materials and components.
Cost of silicon carbide

A significant portion of the cost of MMC materials is in the raw material expenses (the aluminum, alloying elements, and reinforcement). Current castable aluminum MMC typically utilizes an F-500 grade of high-purity green SiC. The F-500 designation refers to the sorting and classification that establishes a well-defined particle size distribution. Because the F-500 SiC reinforcement is sorted and sized, and a surface treatment is applied, the additional processing adds cost. To help further reduce the cost beyond that made possible by the rapid mixing and compositing method alone, an alternative, lower-cost, black SiC material has been utilized. This grade of SiC has lower purity than the green SiC, and has a wider size distribution. Since the sorting and pretreatment requirements are relaxed, the manufacturing time is lower. Despite the lower purity of the SiC and the wider size distribution, this material is adequate for reinforcement of MMC.

Estimated cost for black SiC supplied at moderate to high volumes is less than $2.20 per kg. This is approximately half of the cost of the F-500 grade. The lower cost SiC results in a cost savings of $0.48 per kg for aluminum MMC with 20 vol% SiC. The total estimated MMC material cost for the production of a 359/SiC/20p product, utilizing the MC-21 rapid mixing process and lower cost SiC, is approximately $2.40 per kg. This, combined with further cost savings from the reduction in ingot shipping charges and labor time associated with remelting, could drive costs even lower, and represents an enabling step forward in more widespread applications of aluminum MMC.

For more information: Darrell Herling, Senior Development Engineer, Pacific Northwest National Laboratory, 902 Battelle Blvd., MS: P8-35, Richland, WA 99352; tel: 509/376-3892; fax: 509/376-6034; e-mail: darrell.herling@pnl.gov.

This project was funded by the Department of Energy, Office of Transportation Technologies, Office of Advanced Automotive Technologies. The authors would like to thank David Schuster and Mike Skibo at MC-21, Inc. for their involvement in this project and providing the materials for evaluation. The Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC06-76RLO 1830.

How useful did you find the information presented in this article?

Very useful, Circle 288
Of general interest, Circle 289
Not useful, Circle 290