N94-30482

CASTING OF WELDABLE GRAPHITE/MAGNESIUM METAL MATRIX COMPOSITES WITH BUILT-IN METALLIC INSERTS

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p 6

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ABSTRACT

This paper describes technology innovations directed at the advanced development of a potentially low cost and weldable graphite/magnesium metal matrix composites (MMC) through near net shape pressure casting. These MMC components uniquely have built-in metallic inserts to provide an innovative approach for joining or connecting other MMC components through conventional joining techniques such as welding, brazing, mechnical fasteners, etc. Morever, the metallic inserts trapped within the MMC components can be made to transfer the imposed load efficiently to the continuous graphite fiber reinforcement thus producing stronger, stiffer and more reliable MMC components. The use of low pressure near net shape casting will be economical compared to other MMC fabrication processes. These castable and potentially weldable MMC components would provide great payoffs in terms of high strength, high stiffness, low thermal expansion, lightweight, and easily joinable MMC components for several future NASA space structural, industrial and commercial applications.

INTRODUCTION

Graphite fibers reinforced magnesium and aluminum are becoming more valuable metal matrix composite materials for aerospace and automotive applications because of their lightweight and high strength properties (1). The current candidate materials for advanced space structural component applications can be listed as beryllium, graphite/epoxy polymer composites, particulate SiC/aluminum MMC, and continuous graphite fiber reinforced aluminum and magnesium MMC. Table 1 presents a qualitative tradeoff analysis on these candidate materials for NASA space structural applications. Beryllium is a very lightweight metal of high specific stiffness but it has safety, cost, fabrication and handling problems. Graphite fibers reinforced polymeric composites are not suited for long exposure in space environment due to chemical reaction with atomic oxygen and deep space radiation. To overcome this problem, an aluminum protective coating can be applied onto the outside surface of these polymeric composites. However, this method not only adds significant processing cost, but it also reduces the component effective stiffness and resistance properties to thermal cycling.

Discontinuous fibers or particulates reinforced aluminum MMC has good resistance to space environment. However, they only provide a small to moderate increase in stiffness and strength performance over the conventional aluminum alloys. Finally, continuous graphite reinforced aluminum or magnesium offers the best material properties for space structural applications. Unfortunately, most graphite reinforced MMC components are prohibitively expensive for most applications due to high cost fabrication techniques such as powder metallurgy, thermal-arc plasma spray and diffusion bonding. These fabrication processes often yield MMC products in simple forms such as metal ingots, wires, thin metal sheets or cylindrical tubes as basic building blocks. The final component applications fabricated from these basic building blocks are often expensive and have limited shape complexity.

The present investigation is concerned with MMC components that can be cast with near net shape dimensional tolerance and at relatively low cost. The casting process can be performed with continuous, chopped or particulate reinforcements infiltrated with molten liquid aluminum or magnesium alloys. The significant advantage of such casting process is that it can produce MMC components with very complex body shapes with little or no requirements for final machining. This paper will focus on the casting of graphite P-100 continuous fibers reinforced magnesium AZ91E alloy.

Table 1. Canditate material systems for advanced NASA space structural applications.

MATERIALS	ADVANTAGES	DISADVANTAGES
Beryllium	• High specific stiffness • No outgassing problems • Very lightweight metal • Low CTE values	• Toxic material • Very difficult to machine • Extremely Notch-Sensitive • High material & fabri. cost
Graphite/Epoxy Composites	• High specific stiffness • Relatively low material cost • Mature technology • Near Zero-CTE value	• Attacked by atomic oxygen • Outgassing problems for optics • Low temperature applications
Particulate SiC/Al MMC	• Moderate specific stiffness over unreinforced metals • Relatively mature MMC tech. • No outgassing problems • Resistance to space environ. • Cast to near net shape parts	• Inadequate specific stiffness & strength for some applica. • Low welding/brazing strength • Relatively high fabrica. cost
Continuous Graphite/Al and Magnesium MMC	• Outstanding specific stiffness • Excellent tailorable CTE values • Cast to near net shape parts • Resistance to space environ. • No outgassing problems • High thermal conductivity	• Poor welding/brazing strength • Relatively high fabrica. cost

As seen in Table 1, in addition to the high cost problems associated with using MMC materials, another major disadvantage is that they can not be joined together easily through conventional joining methods such as welding, brazing or solder. The demand for a standardized and reliable joining method for graphite MMC components has become one of the critical MMC technology requirements. In the past, several MMC joining methods have been evaluated and most of these techniques were concluded as unsuccessful (2). In most cases, the MMC component joint strengths were limited by their low graphite-to-face sheet peel strengths. Under the extreme heat of arc welding, the joint strength can further decrease due to the graphite reinforcement migration into the weld nuggets. To overcome this joining problem, NASA and Foster-Miller, Inc. have developed a joinable graphite MMC through the innovative use of metallic inserts that are made to be permanently trapped within the cast composite components. In this way the metallic inserts can provide a site so that a conventional joining method can be applied directly onto them. The idea presented here is that welding can be done from one metallic insert connected with a metallic insert from another MMC component. Another advantage of using trapped metallic inserts is that they can transfer the imposed load efficiently to the graphite fibers. For example, in the design of a typical clevis joint, metallic inserts can be placed at a specific location within the MMC component to resist the bearing load exerted by the connecting pin and to distribute this axial load over a larger area of the component. Additionally, a certain type of insert materials can be used to greatly enhance the wear resistance of graphite MMC components subjected to unique bearing load applications.

MMC PRESSURE CASTING PROCEDURE

Although MMC pressure casting has been used in various forms over the years, its application to the production of practical components is rapidly growing just within the last 5 years (3,4). The typical equipment used to pressure cast graphite/magnesium MMC components is shown in Figure 1. The device consists of two main components: the pressure vessel and the water-cooled lid. The pressure vessel contains the crucible heater bank and the molten matrix alloy crucible. The water-cooled lid is positioned on top of the pressure vessel and attached to it is the die, its heater bank and the molten matrix transfer tube. There are also feedthroughs for thermocouple wires, power leads, and pressure sensors to this lid. The operating principle of the device is to use an inert pressurized gas to force the molten metal into an evacuated die. Dies can be made from common materials such as ceramics, graphite, quartz glass, and sheetmetals which hold advantages in terms of low cost and easy machinability.

In this study the die for the cast MMC component was machined out of a fine grained low porosity graphite block. Graphite was chosen because of its relatively low cost, easy to machine into complex shapes, low thermal mass and has potential for reusability. Low thermal mass die will allow a close control on the graphite fiber reinforcement temperature prior to molten metal infiltration within the die. A thin boron-nitride coating was applied onto the inside of the graphite die to ease the removal of the cast MMC component after infiltration by molten metal.

To operate the device the water-cooled lid is placed on top of the pressure vessel so that the end of the molten matrix transfer tube is immersed in the molten matrix crucible. Prior to heating the fiber preform and melting the metal alloy contained in the crucible, a vacuum must be drawn within the pressure vessel. This vacuum will help in preventing the molten liquid metal and the fiber preform from oxidizing at high temperature. When the molten metal and the fiber perform have reached the optimum processing temperatures, the vessel is then pressurized with argon gas to force the molten magnesium alloy into the die cavity. When the molten metal reaches the top of the die here it will come in contact with the water-cooled lid. The molten metal becomes solidified immediately and thereby creating a pressure seal for the vessel. With this seal on top of the die the pressure vessel can now be pressurized up to 800 psi with argon gas to force the molten magnesium into the die cavity for a complete infiltration of the graphite fiber reinforcements. Temperature and pressure are the two most important casting process parameters. Therefore, the crucible molten metal and the die cavity heater banks must be interactively controlled so that one can achieve a unique casting process condition. These parameters are critical to the quality and reproducibility of the cast MMC parts. Failure to optimize these parameters can result in many cast defects such as porosity, incomplete infiltration, oxide inclusions, excessive reaction of graphite fibers with matrix alloy, etc.

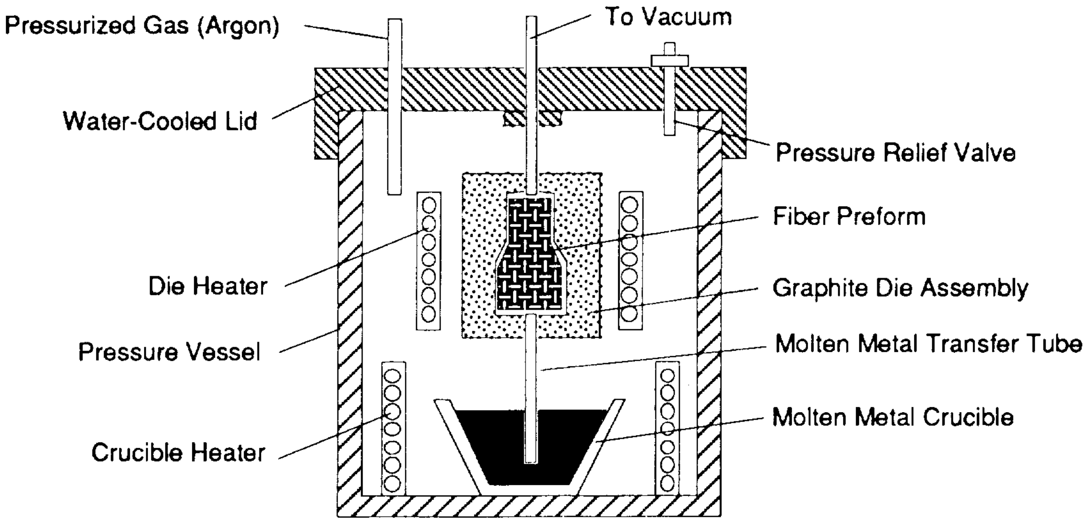


Figure 1. Schematic diagram for a typical MMC pressure casting apparatus.

COMPONENT SELECTION AND INSERT DEVELOPMENT

A representative clevis tube end-fitting component was selected as the demonstration article for this effort. This design was selected after performing a quantitative tradeoff analysis of various joint component candidates for potential use in NASA future space truss and commercial applications. Figure 2 shows a typical clevis joint of 4.5 in. long by 2.0 in. diameter and 0.25 in. wall thickness. This component has a moderately complex shaped body for a near net shape casting demonstration. In this design a continuous fiber perform was needed to provide a high axial stiffness in the clevis region and a high torsional stiffness in the tube region. To achieve the optimum fibers alignment within the cast a continuous fiber preform was developed using P-100 graphite fibers that were wound at plus and minus 45 degrees over a salt mandrel. These fibers come from a 0.25 in. wide by 0.005 in. thick graphite fiber tape with a polyethylene binder. This binder was used to hold the graphite fibers together during the casting process and it will decompose during the die heat up and leave no discernible residue within the cast component. The mandrel was machined from a cold isostatically pressed (CIPed) sodium chloride powder. From the previous experimental works this salt mandrel design was proven to be impervious to pressurized molten magnesium or aluminum alloys and washes out easily after casting (5).

To make such cast MMC components weldable, for easily joining through conventional welding or brazing technique, we incorporated metallic inserts that are made to be permanently trapped within the cast composite components. In this way the metallic inserts can provide a site so that conventional joining method can be applied directly onto them. The idea presented here is that welding can be done from one metallic insert connected with a metallic insert from another MMC component. As shown in Figure 2, this clevis joint has two different types of built-in metallic inserts. One type was used to facilitate easy joining while the other type of insert was used to enhance the load carrying capability of the cast component. At the tube end, the "joining insert" provided a metallic surface for joining to the neighboring component (not shown) by conventional metal joining techniques. At the clevis end, the "load transfer insert" was positioned at a specific location to resist the bearing load exerted by the connecting pin and to distribute this axial load over a larger area of the component.

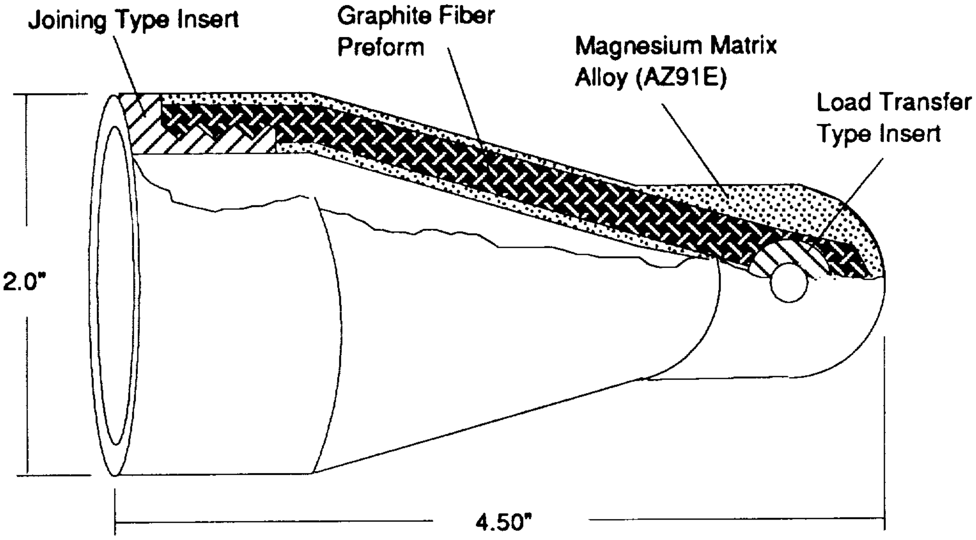


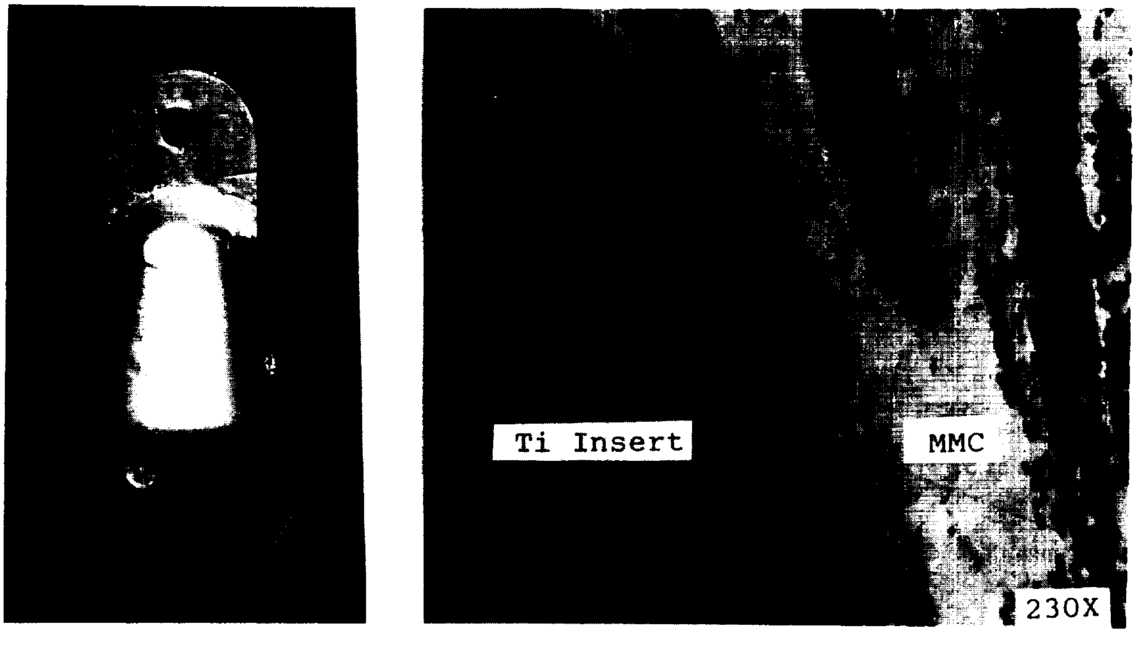
Figure 2. A clevis-joint component with moderately complex shaped body was selected for a near net shape casting demonstration. Note that this joint has two different types of built-in metallic inserts. One type is used to facilitate easy joining while the other insert is used to enhance the load carrying capability.

In the development of metallic inserts the selection of insert materials and their machined profile shapes are the two most important design parameters. To create a strong bond between the insert and the matrix metal the insert materials must be selected such that their liquidus and solidus temperatures are close to the infiltration temperature from the molten magnesium. Various candidate materials for inserts were selected and tested during casting trials. For instance, if one uses an aluminum alloy insert, due to its low melting temperature, this insert may completely melt during the infiltration process. On the other hand, the major concern regarding the use of titanium insert is the propensity to form unwanted brittle intermetallic phases and thereby degrading the load transfer capability of the MMC component.

The second design parameter for the metallic inserts is the cross sectional profile shape in which the insert is expected to fit and anchor firmly in the MMC component and to transfer the load evenly across the insert/MMC interfaces. A typical profile of the insert consists of a rippled outer surface such that the continuous graphite fiber reinforcements can wrap around it prior to infiltration. The higher the ripple surface angle the more area will be made available for the fiber bundles to anchor themself firmly into the insert. However, such high ripple surface contour will result in minimum bending radius for the graphite fibers to bend around a typical anchoring corner which thereby can cause an unacceptable amount of fiber breakage within the fiber bundles in the preform. Although there is an optimum height for the ripple surface contour, the depth of this surface curvature is limited by the overall thickness of the metallic insert. Usually, the insert thickness is kept very minimum so that its weight is relatively small when comparing to the total weight of the MMC component.

RESULTS AND DISCUSSION

Figure 3a is a photograph showing the result of the cast near net shape graphite/magnesium MMC component with built-in metallic inserts for easy joining and better load transfer. The photograph shows that low pressure process can produce net shape casting of complex shaped MMC components using low cost materials and toolings. Cast MMC components evaluation were performed by static tensile testing and followed by optical microscopic examination.



(a) (b)

Figure 3. Photograph (a) shows the final result of the near net shape casting of graphite/magnesium MMC component with built-in titanium inserts. Photograph (b) at 230X magnification shows no cracks nor reaction zone at the interface between the titanium inserts and the MMC material.

Several graphite/magnesium cast components was subjected to static mechanical testing to assess the structural integrity of the MMC at the metallic insert interface. By using adhesive bonding, one end of the clevis component was connected to a cylindrical loading rod at the metallic insert interface. At the other end of the clevis joint, a loading pin was used by placing it through the clevis end loading hole. The tensile tests were conducted by attaching the cylindrical loading rod and the loading pin to the tensile testing machine so that the clevis component will be pulled away, under applied tensile stress, from the cylindrical loading rod. Test results showed that metallic inserts located at the tube end and at the clevis end region effectively transferred the axial load to the graphite fiber reinforcements because the MMC component failure mode occurred within the MMC material and away from the MMC/insert interface. The tensile test did demonstrate the feasibility of the cast MMC component with built-in metallic inserts since the failure site did not occur at or near the insert locations.

To perform microstructural analysis, sections of the component were cut and polished for observation under microscopic examination. Sections of MMC component around each metallic insert were evaluated for bonding strength, interactions with the insert materials, as well as fiber distribution, void content, and fiber damage, if any. Figure 3b shows the micrograph (at 230X magnification) of the interface between the titanium insert and the graphite/magnesium MMC material. This interface between titanium insert and magnesium matrix alloy did not show any formation of the intermetallic phases. These unwanted brittle phases would have degraded the mechanical properties of the component at the joint. Moreover, after the tensile tests were performed, as shown in figure 3b the interface between the insert and the magnesium matrix is also free of cracks, voids and fiber degradation. In summary, the cast MMC component exhibited excellent mechanical properties with complete molten metal infiltration under pressure casting technique as described in this investigation.

CONCLUSION

To encourage the widespread utilization of future MMC components in industrial and commercial markets, one must find a way to reduce the MMC component cost and develop better joining techniques. This paper describes a feasibility demonstration of a low cost pressure casting for a complex shaped MMC component with built-in metallic inserts to facilitate easy joining and better load transfer. The low cost factor was achieved through the use of near net shape casting in which the machining requirement to produce the component shape is significantly reduced or eliminated completely. From the microstructure analysis the cast MMC component exhibited complete molten metal infiltration of the fiber reinforcements and showed defect free at the interface between the metallic inserts and the MMC material. The component joint strength was tested through the use of adhesive bonding applied at the insert surfaces. The tensile test did demonstrate the feasibility of the cast MMC component with built-in metallic inserts since the failure site did not occur at or near the insert locations. In general, the tensile tests performed in this investigation proved that the joint strength at the insert/MMC interface is greater than the overall strength of the graphite/magnesium MMC materials within the cast component.

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