DEVELOPMENT OF METAL MATRIX COMPOSITES FOR NASA'S ADVANCED PROPULSION SYSTEMS

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ABSTRACT

The state-of-the-art development of several Metal Matrix Composites (MMC) for NASA's advanced propulsion systems will be presented. The goal is to provide an overview of NASA-Marshall Space Flight Center's on-going activities in MMC components for advanced liquid rocket engines such as the X-33 vehicle's Aerospike engine and X-34's Fastrac engine. The focus will be on lightweight, low cost and environmental compatibility with oxygen and hydrogen of key MMC materials, within each of NASA's new propulsion application, that will provide a high payoff for NASA's Reusable Launch Vehicles and space access vehicles. In order to fabricate structures from MMC, effective joining methods must be developed to join MMC to the same or to different monolithic alloys. Therefore, a qualitative assessment of MMC's welding and joining techniques will be outlined.

INTRODUCTION

In this paper, the state-of-the-art development of Metal Matrix Composites (MMC) for NASA's advanced propulsion systems will be presented. The focusing theme will be on lightweight, affordable and environmental compatibility with oxygen and hydrogen of key MMC materials that will provide a high payoff for NASA's reusable launch vehicle systems and space access vehicles. Historically, MMC has been used for NASA's flight hardware such as boron fibers reinforced aluminum struts for the Space Shuttle's mid-fuselage in 1982, and graphite fibers reinforced aluminum antenna for the Hubble Space Telescope in 1990 (ref. 1). However, these types of MMC were costly to produce and were not developed specifically for propulsion systems.

In recent years, Marshall Space Flight Center (MSFC) has been focusing on the development of low cost and lightweight components using net shape casting for advanced propulsion systems, which commonly have high density copper alloys and superalloys. In order to improve the engine thrust-to-weight ratio for advanced launch vehicles, lighter materials with new fabricating methods must be developed using concurrent engineering method (ref. 2). MMC are often valued for their "tailor-ability" property, which dictates a specific MMC formation for a specific application. For this reason, complexity and cost for the development of an MMC property database can often be more than for a conventional alloy database, which favors a "commodity" approach. In the commodity approach, the conventional practice is based on one single alloy formulation to be used for many structural applications. For MMC, material specialists and engine's designers must work closely during the early phases of the program to develop a specific MMC property database for a specific application. As part of the planning stage, the Technology Readiness Level (TRL) for material, joining processes and the cost affordability factor have become important development issues for MSFC's material selection strategy.

MATERIAL AND PROCESS SELECTIONS

Material Selections

Technology assessment has shown that Discontinuously Reinforced Aluminum (DRA) MMC can become viable candidate materials for propulsion applications in cryogenic and near ambient temperatures. Evidently, the development cost for DRA is affordable and the TRL is relatively high such that production of complex DRA components have been applied for the auto industry with high dimensional tolerance and minimal machining requirements (ref. 3, 4, 5). Figure 1 shows the comparison for the specific stiffness (modulus/density) of DRA, which is better than most conventional superalloys being used in propulsion hardware. DRA also acquire its toughness and ductility from the aluminum and will behave more like conventional aluminum alloys due to its isotropic properties (ref. 6, 7). On the other hand, isotropic property also means that DRA would tend to have lower specific strength value (strength/density) as compared with Continuously Reinforced Aluminum (CRA) with fibers such as silicon carbide, aluminum oxide, etc. Therefore, the selection strategy is to substitute DRA for stiffness-driven applications and CRA for strength-driven and unidirectional loading applications at cryogenic and near ambient temperatures.

Similarly, copper MMC can become viable candidate materials for oxygen-rich environment at relatively high temperatures and pressures. However, copper MMC have not been extensively used for commercial applications as compared with aluminum MMC. Technology assessment of nickel and copper MMC programs, funded by the DoD and NASA in recent years, indicated that these high temperature MMC are not as "mature" as aluminum MMC (ref. 8, 9). However, the current development for Discontinuously Reinforced Copper (DRC) appears to be more viable technology than Continuously Reinforced Copper (CRC) for certain types of stiffness-driven applications in oxygen-rich environment.

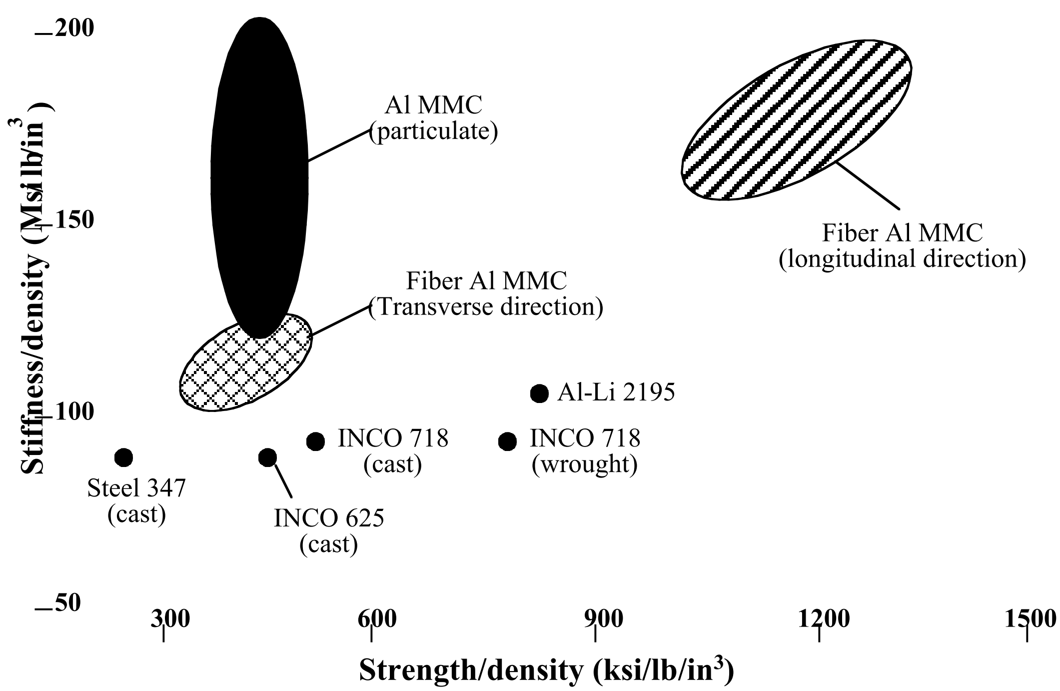

Figure 1. Plot of specific stiffness versus specific strength for Al MMC.

Process Selections

Similar to material selection, the strategy for process selection is based on low cost and capability for net shape fabrication with minimal machining and welding requirements. In order to evaluate these fabricating processes as a function of component applications, forms (shapes) and materials, a ranking matrix is developed for the fabricating processes, which can be classified into 7 classes as shown in Figure 2. Each of these techniques consists of unique features that are grouped in terms of applications, product forms and materials. For example, diffusion bonding is a choice method for continuous fibers MMC, which is applicable for unidirectional loading applications such landing gear, struts, beam, etc. Historically, diffusion bonding has been used for NASA's flight hardware such as MMC struts for the Space Shuttle's mid-fuselage and antenna for the Hubble Space Telescope. However, these types of MMC were costly to produce and not directly applicable for making complex near net shapes such as turbopump housings. In summary, pressure infiltration and gravity casting were selected as primary level processes because they are the most versatile for producing complex net shape components with relatively low processing cost. Secondary processing level would be selected as spray deposition and centrifugal casting for fabricating of simple net shape components. Finally, powder metallurgy and laser 3D deposition processes are selected as a third level for wrought products for airframe applications with near isotropic properties. In some instances, powder metallurgy can be used to produce simple net shaped components. Currently, Laser 3D deposition is an emerging technology with limited data for MMC assessment.

Relative Cost

High ← **Low**

MMC's Fabricating Methods

	REQUIREMENTS	Diffusion bonding	Powder metallurgy	Laser 3D deposition	Spray deposition	Pressureless Infiltration	Pressure Infiltration	Gravity Casting
Applications	Ultra-high strength	●					●	
	Ultra-high stiffness	●	●		●		●	
	Moderate strength	●	●	●	●	●	●	●
	Moderate stiffness	●	●	●	●	●	●	●
	Isotropic properties		●	●	●	●	●	●
	Wear resistance		●	●	●	●	●	●
Product Forms	Thick plates & blocks		●		●		●	●
	Thin plates & sheets	●	●	●	●	●	●	
	Large cylindrical shells	●			●			
	Tubes, rods & beams	●	●		●	●	●	●
	Simple near net shapes	●	●	●	●	●	●	●
	Complex near net shapes			●			●	●
Materials	Continuous fibers & tapes	●					●	
	Chopped & short fibers				●		●	●
	Particulate & whiskers		●	●	●	●	●	●
	Hybrid systems				●		●	●

Figure 2. Qualitative assessment for MMC fabricating methods.

ENVIRONMENTAL COMPATIBILITY

The material compatibility with oxygen and hydrogen environment has always been an important issue for rocket propulsion systems (ref. 10). Preliminary assessment has shown that aluminum alloys and aluminum MMC are considered to be compatible with oxygen environment only at low pressure (<1500 psi) and cryogenic temperature. Therefore, aluminum MMC can be used for ducts, flanges and turbopump housings that operate at cryogenic temperature and low pressure. From near ambient temperature up to about 900 F, copper-based MMC are compatible with high pressure oxygen-rich environment. The development of copper alloys reinforced with aluminum-oxide particulate and/or fibers, have shown to be compatible with oxygen environment. On-going efforts are under way at MSFC to characterize the material compatibility issues in an oxygen-rich environment for aluminum and copper based MMC. Currently, titanium based MMC are not recommended for oxygen environment even at cryogenic temperature. For hydrogen environment, aluminum and copper-based MMC are shown to be compatible in a wide range of operating temperatures and pressures. However, some titanium MMC are compatible with hydrogen only at cryogenic temperatures. In contrast with polymer matrix composites, the hydrogen permeation is not an issue for most metals and MMC. This is an important compatibility factor for MMC in the design consideration of ducts, flanges and pressure vessels for hydrogen containment applications.

COMPONENT SELECTION FOR DEMONSTRATION

Flanges for Fuel Line

There is a significant amount of mass associated with the usage of superalloy's ducts and flanges for the fuel feed lines of the X-33's Aerospike engine. The ducts are identified as strength-driven components, which will be made from lightweight nanophase aluminum or aluminum-lithium alloys in the future. The flanges are stiffness-driven components, which are ideal targets for weight reduction using particulate reinforced aluminum MMC such as boron carbide (B_4C), silicon carbide (SiC) or aluminum oxide (Al_20_3). With SiC reinforced aluminum MMC, a 55% mass reduction over conventional IN 625 can be expected for each of the flanges. Significant total weight reduction can be expected since there are approximately 36 flanges for the combined oxygen and hydrogen side for the feed lines of the Aerospike engine. The potential technical issue is to develop appropriate techniques for joining the aluminum-lithium, aluminum alloys or nanophase aluminum ducts to Al MMC flanges. Figure 3 shows several prototype aluminum MMC flanges that were produced by Metal Matrix Cast Composites (MMCC) Inc. using advanced pressure infiltrated casting.

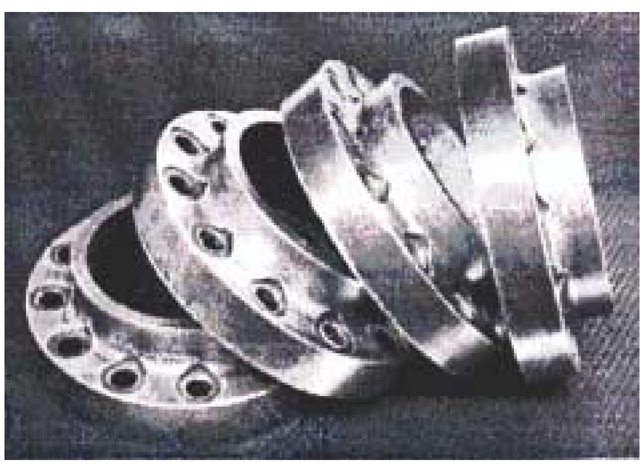

Figure 3. Al MMC prototype flanges for X-33's fuel line ducts.

X-33 Engine's Thrustcell

The X33's aerospike engine consists of several thrust cells which can comprise as much as 25% of the engine weight. The interior wall of the thrust cell chamber is exposed to high temperature combustion products and must be cooled by using liquid hydrogen. Currently, the structural jacket and manifolding of the thrust cell chamber is made of stainless steel (SS) 347, which can potentially be replaced with a lighter material by using aluminum MMC. Up to 50% mass reduction over conventional SS 347 can be expected for each of the thrust cell chambers using MMC. To demonstrate the level of maturity for aluminum MMC technology, several MMC chambers have been produced using gravity casting and plasma spray deposition process. In addition to MMC, a new copper alloy (Cu-8Cr-4Nb), that has higher strength than the traditional copper alloy of NARloy-Z for chamber liners, is also being investigated in this program. Currently, several thrust chamber design concepts are being worked to resolve the potential technical issue of bonding or brazing the liquid hydrogen cooled Cu-Cr-Nb liner to the surrounding MMC jacket. For instance, Figure 4 shows an MMC chamber, made from an Al/SiC MMC jacket, which is cast around a copper liner in a "one-step" brazing-casting process under gravity casting by MSE Technology Applications, Inc.

Figure 4. Al MMC prototype "lightweight" thrust chamber for thrust cell applications.

X-34's Turbopump Housing

Preliminary analysis has shown that up to 40% mass reduction over conventional cast INCO 718 superalloy can be expected for the X-34's Fastrac engine turbopump housing. The candidate material under consideration is a hybrid aluminum MMC system that consists of a mixture of aluminum oxide (Al_20_3) continuous fibers and Al_20_3 particulate. For this reason, the key material challenge is to develop a capability to manufacture hybrid MMC, with selectively reinforced fibers for high strength in proper high stress locations, using pressure infiltrated casting. This Al MMC technology is targeted for new hydrogen or hydrocarbon turbopumps and is also applicable to low-pressure oxygen turbopump at cryogenic temperature. If successful, many rocket systems such as the Venture Star, Long Life Bantam engine variations and rocket based combined cycle systems will benefit by the weight reduction achieved from this Al MMC for the X-34's turbopump housing demonstration program. Figure 5 shows a half-scale X-34's turbopump housing which was produced by MMCC, Inc. using advanced pressure infiltration casting of aluminum alloy reinforced with 50% by volume of aluminum oxide particulate.

Figure 5. Half-scale Al MMC turbopump housing for X-34's Fastrac Engine.

<u>Al MMC ducts</u>

Preliminary analysis of cryogenic feedlines and ducts has indicated that up to 30% weight redution can be achieved by using MMC reinforced with continuous alumina fibers. This is based primarily on the hoop strength of such a brazed aluminum composite relative to the strength of an Inconel feedline as used on the X-34 vehicle technology demonstrator. Under NASA sponsorship, this novel MMC material tape concept has been developed by Touchstone Research Laboratory (TRL), for making lightweight MMC ducts from prepreg unidirectional tape produced by 3M. This unique MMC prepreg unidirectional tape form can be laid-up as plies with the plies oriented to meet the component performance requirements in an analogous manner to polymer matrix composites. These plies can then be consolidated using TRL's patented brazing process. Theoretically, TRL's solution incorporates a very thin MMC tape with an automated brazing technique that combines the ability to produce propellant feedlines with inherent low cost of polymer manufacturing technique but it could achieve a better interlaminar strength than polymer composites. This technology demonstration of brazed continuous aluminum MMC tape for propellant feedlines and ducts could have direct application to cryogenic tanks and airframe structure as well. Figure 6 shows a small section of a cryogenic duct that is produced by using a continuous in-situ brazing process for a 2-ply hoop wound cylindrical section with a diameter of 5 inches.

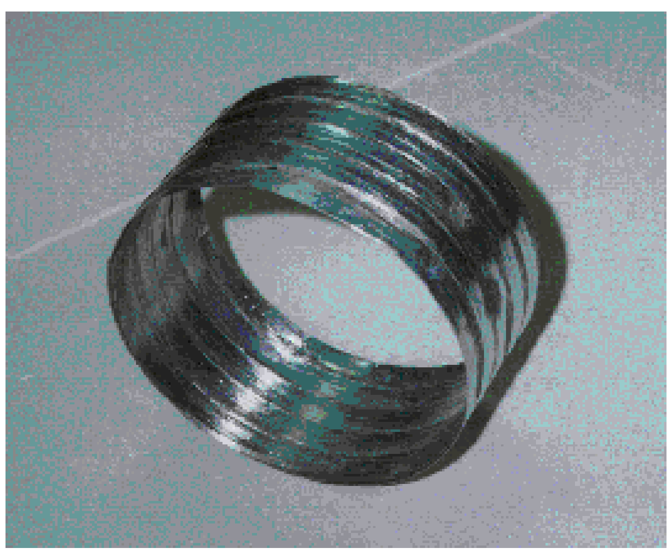

Figure 6. A small section of a cryogenic duct produced by brazing MMC tape.

QUALITATIVE ASSESSMENT FOR JOINING TECHNOLOGIES

In order to fabricate structures from MMC, effective joining methods must be developed to join MMC to the same or to different monolithic alloys. Since MMC utilize a variety of non-metallic reinforcements, they will naturally impose limitations for joining using conventional methods from monolithic metals. As a general rule, the adaptability of any joining techniques for MMC will depend on the combination of the following factors: (1) the volume percent amount and types of reinforcements, (2) metal matrix melting point, and (3) the thermal energy management from the selected joining process. Discontinuously reinforced MMC are easier to join than continuously reinforced using fibers, which are prone to matrix-fiber de-bonding, de-lamination, non-uniform fiber packing density and migration of fiber bundles into the weld regions. The prolonged contact time between a molten metal matrix and a reinforcement can lead to undesirable chemical reactions, which are accelerated as the molten metal temperature increases. Although high thermal energy is required for most conventional joining processes, excessive thermal energy input is undesirable. For this reason, the higher the metal matrix melting temperature the less likely for most of the fusion techniques to be applicable for MMC. A qualitative assessment of the adaptability of 17 monolithic joining techniques to MMC is summarized in Figure 7 (ref. 11). It is important to realize that MMC joining is not a mature technology and many important joining technical details are still lacking. Consequently, the adaptability for a specific joining method is a specific material and process factor which must be determined experimentally (ref. 12, 13).

Joint Applications

Joining Methods	Strength driven	Stiffness driven	High temperature	Thermal conduction	Electrical conduction	Dimensional stable	Complex shapes	Dissimilar materials	**Adaptable to MMC**
Inertia friction welding	○	○	○	○	○	▨	●	▨	○
Friction stir welding	○	○	○	○	○	▨	●	▨	○
Ultrasonic welding	○	○	○	○	○	○	●	●	○
Diffusion bonding	▨	○	○	○	○	○	○	▨	○
Transient liquid phase	▨	○	○	○	○	○	○	▨	▨
Rapid infrared joining	▨	○	○	○	○	○	▨	▨	▨
Laser beam welding	○	○	○	○	○	▨	▨	●	●
Electron beam welding	○	○	○	○	○	▨	▨	●	●
Gas metal arc welding	○	○	○	○	○	▨	○	●	●
Gas tungsten arc welding	○	○	○	○	○	▨	○	●	●
Resistance spot welding	○	○	○	○	○	▨	▨	●	▨
Capacitor discharge	○	○	○	○	○	▨	▨	●	▨
Brazing	▨	○	▨	○	○	▨	○	▨	▨
Soldering	▨	▨	●	▨	○	○	○	▨	○
Adhesive bonding	●	▨	●	●	●	○	○	○	○
Mechanical fastening	○	▨	○	▨	○	▨	○	○	○
Cast-insert joining	○	▨	○	▨	○	▨	▨	○	○

Joint Performance Rating: ○ High ▨ Medium ● Low

Figure 7. Qualitative assessment rating for MMC joining methods.

CONCLUSIONS

Technology readiness level for materials, joining processes and the cost affordability have become important issues for NASA in developing MMC for advanced propulsion systems. Discontinuously reinforced aluminum (DRA) are viable candidate materials for propulsion applications and they can be substituted for component with stiffness-driven applications at cryogenic and near ambient temperatures. Similarly, copper MMC are viable candidate materials for in oxygen-rich environment at relatively high temperature and pressure. A qualitative assessment for joining methods has shown that the use of solid state and low temperature processes are often more adaptable for joining of MMC than the use of high temperature fusion processes.

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