Metal Matrix Composites Synthesized with Laser-Based Additive Manufacturing

Steven M. Storck, Ian D. McCue, Timothy J. Montalbano, Salahudin M. Nimer, and Christopher M. Peitsch

ABSTRACT

Metal matrix composites (MMCs), with their unique property combinations, have the potential to enable disruptive capabilities for extreme environment applications that require high performance from materials. A Johns Hopkins University Applied Physics Laboratory (APL) team successfully produced an aluminum-silicon carbide system with additive manufacturing (AM). The team also demonstrated the ability to grade the metal and ceramic three-dimensionally to form tailored material gradients. This effort merely scratches the surface of what is possible; future advances in AM materials development could result in materials with properties that are currently impossible to achieve with any other manufacturing process. These materials could benefit many applications.

For defense applications in particular, there is a constant demand to improve the performance of materials in extreme environments.[1–3] The past few decades have seen significant progress in material development (e.g., Ni-base superalloys and ultra-high hardness ceramics) for extreme application spaces such as hypersonics and ballistic impact.[4–7] However, to continue increasing performance at the current rate, we need to develop new materials with both dramatic property enhancements and unique property combinations—for example, high specific strength and conductivity.[8–11]

With their unique property combinations, metal matrix composites (MMCs) have the potential to disrupt these extreme application spaces.[12,13] When properly designed, MMCs blend the best physical properties of metals (high ductility, work hardening rates, and conductivity) with those of ceramics (high stiffness, strength, and low density).[8,13,14] These property combinations can yield materials that operate in regions of Gibson–Ashby charts (e.g., high specific strength and conductivity) and that are unattainable with conventional metallic or ceramic materials alone.

Despite the disruptive potential of MMCs, the major impediment to their widespread use is synthesis and processing,[13,15] as illustrated in Figure 1. It is exceedingly difficult to use traditional manufacturing methods to synthesize MMCs at any fabrication stage. Uniformly dispersing a ceramic phase into a molten metal matrix (i.e., stir casting) is notoriously challenging and becomes more difficult with increasing ceramic volume fraction; metal–ceramic interfaces tend to be incoherent and weak unless carefully grown via physical vapor deposition. Moreover, it is nearly impossible to post-process machine and thermomechanically work MMCs because metals and ceramics have such disparate properties.

A number of these processing challenges could be overcome with nonphysical contact techniques such as laser-based processing[14,16–18] by leveraging the unique

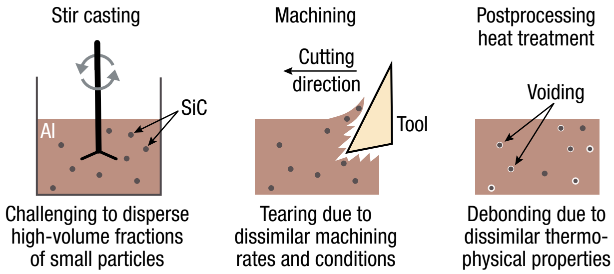

Figure 1. Processing challenges in MMCs. Challenges persist across all stages of production: synthesis (e.g., stir casting), machining, and thermomechanical processing (e.g., heat treatments).

laser–material interactions, temperature gradients, and kinetics inherent to the process. Selective laser melting (SLM) may be the ideal way to produce particulate-based MMC because of its tool-less free-form fabrication and locally configurable energy control. Figure 2 shows how a blended ceramic–metal powder bed could be used to generate a ceramic-reinforced material with minimal modification to the existing SLM process.

SLM is an additive manufacturing process where metal powders are locally melted layer by layer to generate a part to shape or near net shape. This process lends itself well to producing particulate-reinforced MMCs because they can be incorporated volumetrically into the powder feedstock and consolidated under laser melting, shown graphically in Figure 2. Currently, additively manufactured MMCs can be produced less expensively than conventionally manufactured MMCs. Furthermore, additively manufactured MMCs are actually cheaper than an equivalent metal part produced via SLM since the reinforcements are often cheaper than the metal powders used. In addition, the additive process enables gradient material manufacturing because of the layer-by-layer process by which parts are made. Each layer can potentially have a different raw material composition.

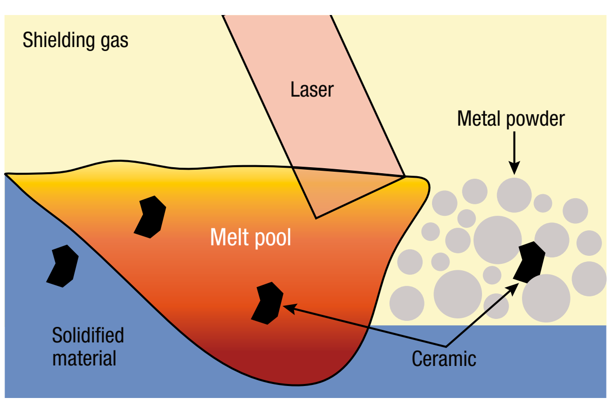

Figure 2. Graphical depiction of a hybrid metal–ceramic powder mixture used in SLM. This blended powder bed can be used to generate a ceramic-reinforced material with minimal modification to the SLM process.

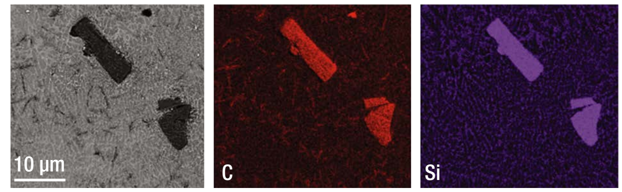

Figure 3. Images showing that APL's SLM system was able to produce Al-SiC MMCs. A scanning electron microscopy image and the corresponding elemental maps from energy-dispersive x-ray spectroscopy of the solidified Al-SiC MMC formed via SLM.

For this project, we chose an aluminum-silicon carbide system since these MMCs have been some of the most frequently used in conventional manufacturing because of their high stiffness and high wear resistance. They have been used in armor, automotive, aerospace, and other applications. Although this type of MMC system is one of the most-used in industry, its implementation is still limited because of the high cost of producing net shape components from MMCs using traditional processes.

Using the aluminum-SiC system, APL fabricated materials via SLM. A scanning electron microscopy image and energy-dispersive x-ray spectroscopy map is shown in Figure 3. This map shows the intermixing of the ceramic SiC phase in the aluminum matrix, demonstrating the capability of producing Al-SiC MMCs with our SLM system.

In addition to improving the mechanical properties, the ceramic additions offer a unique benefit to the SLM process. These particles act as nucleation sites, improving solidification and eliminating directional-edge-based solidification (Figure 4). This means that materials that would conventionally crack under the SLM process, such as the attractive aerospace aluminum AL7075, can

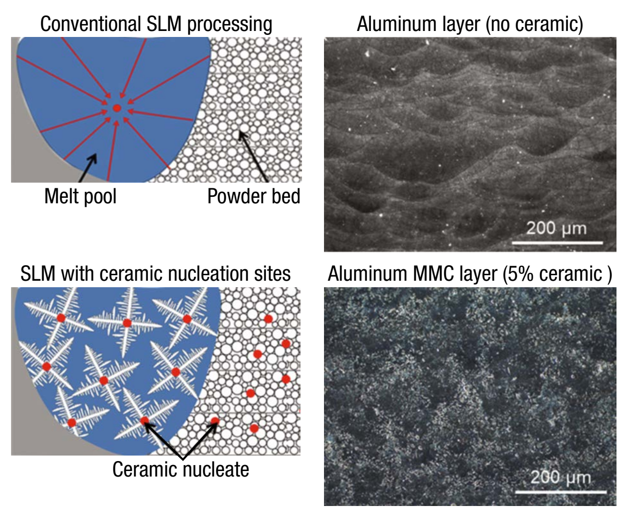

Figure 4. A dark-field microscopy comparison of the microstructure of a conventional SLM material compared to an MMC material. The unique melt pool structure to SLM can be seen in the non-ceramic material where it is absent in the MMC.

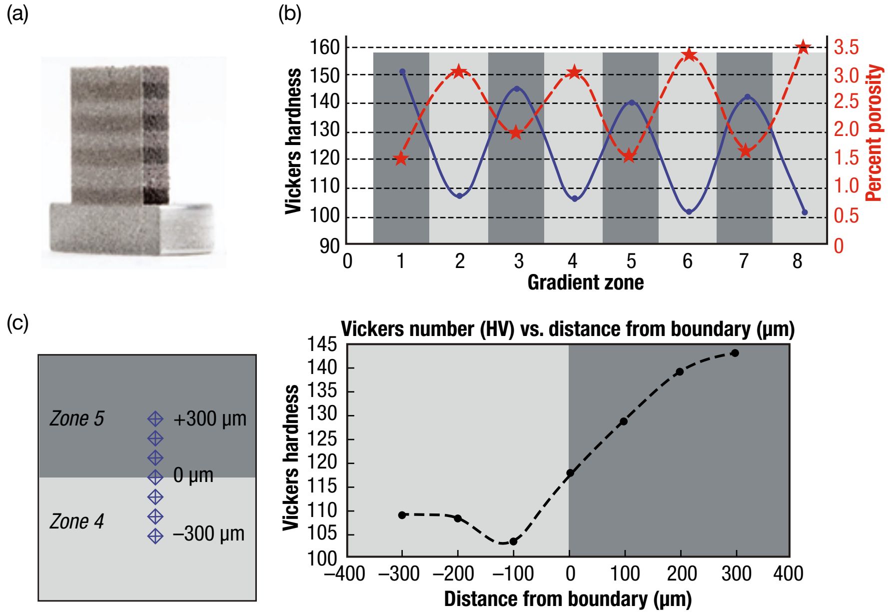

Figure 5. An example of a z-direction gradient material. (a) A gradient material with a 5% SiC reinforced aluminum and pure aluminum. The color change between the layer is visible (dark, MMC; light, aluminum). (b) X-ray computed tomography analysis and hardness testing was conducted on the gradient sample and shows both improved porosity and hardness inside of the solidified MMC layers and a large hardness change between the base metal and MMC. (c) Hardness measurements across the MMC–metal interface.

now be produced. The benefits are not limited to producing crack-free materials. The elimination of the melt pool—a result of more uniform solidification—also helps to solve other unique metal SLM AM problems such as segregation of alloy elements in the melt pool boundary. This segregation can result in detrimental effects such as excessive corrosion in some additive manufacturing–deposited steels.

Since the additive manufacturing process is a layer-by-layer building process, gradient materials were a natural progression for the project. Figure 5 shows an example of a z-direction gradient material. In this case, the eight-layer gradient structure was produced by alternating between a 5% SiC aluminum MMC and pure aluminum in 1-mm gradient thicknesses. To achieve this result, twenty 50-mm SLM layers were built out of a single composition and then a material change was implemented for the next 20 layers and vice versa until the build was completed. The dark layers are 5% SiC reinforced aluminum, and the lighter layers are pure aluminum with no ceramic reinforcement. This gradient configuration has many benefits, one of which is the ability to tune the wave speed in the material based on the acoustic mismatch of the layers. This would be beneficial for reducing the signature of the material in a working fluid.

The z-direction gradient sample was analyzed for porosity using x-ray computed tomography to look for internal porosity, and Vickers hardness testing was performed to show mechanical performance. As shown in Figure 5b, in the ceramic layer the porosity (~100%) is reduced and the hardness is increased (~39%), indicating improved manufacturability and mechanical performance. These data highlight the benefits of additive manufacturing of MMCs.

The stark transition traditionally exhibited with a change of material composition often localizes failure, as the interface is the weak link. As such, investigating the quality of the interface between the base metal and the MMC is critical. Figure 5c shows the hardness map across the additive-manufactured MMC–metal interface. The buoyancy of the ceramic particles is thought to result in a smooth transition between the hardness because of slight compositional variances at the interface.

Figure 6 shows a 1-mm-scale tension sample across the MMC–metal interface. The sample fails within the base aluminum metal, indicating that the MMC and interface are not the weak part of the system. The digital image correlation shows strain localization in the base aluminum layer, indicating that the ceramic reinforcement significantly improves the mechanical response.

This process is not limited to only z-direction or layer-based gradients. An x-direction gradient has also been demonstrated, which enables tailoring in multiple directions in the part. This can unlock spatial tailoring independent of part build direction and can open the technology to a number of applications, from thermal control to wear resistance, where the MMC might only be desirable in certain locations to tailor the physical response.

In conclusion, APL has demonstrated the ability to produce MMCs with additive manufacturing. The work

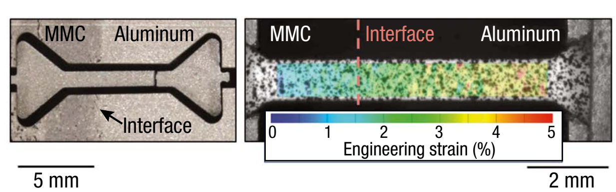

Figure 6. A millimeter-scale tension sample. Shown is a dog bone sample across the MMC interface with respective strain in the gauge. The failure occurs in the base metal, indicating that the MMC and interface are not the weak link in the system.

described in this article merely scratches the surface of what is possible. Future advances in materials development could result in materials with properties that are not possible to achieve with any other manufacturing process. These breakthroughs will enable development of more advanced systems with increased performance, such as lightweight materials with unprecedented high-temperature capability, heat exchangers with two to three times the conductivity of pure copper, and materials that are orders of magnitude better at corrosion resistance. These improvements could benefit many applications, such as aerospace components with direct ceramic portions, possibly eliminating the need for coating; acoustically quiet systems with tailored dampening; and lightweight higher-performance nuclear shielding, to name just a few.

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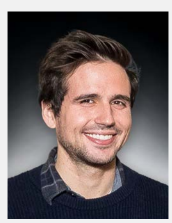

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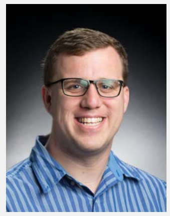

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