# Metal-Monolithic Ceramic/Metal Composite Castings Produced Using 3D Printed Sand Molds and Cores

A.P. Druschitz*, C.B. Williams**, B. Wood***

*Department of Materials Science and Engineering, Virginia Tech, Blacksburg, VA, 24061
**Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA, 24061
***3ExOne, North Huntingdon, PA 15642

## ABSTRACT

Monolithic ceramic and/or metallic objects can be embedded into metal castings using 3D printed sand mold and core technologies. The resulting composite castings can have a combination of mechanical and/or physical properties that cannot be obtained in a single material component. Lattice structures are lightweight and have desirable energy absorbing characteristics since energy is "slowly" dissipated as the structure collapses or fractures. Dissipation of energy over a "long" period of time is desirable for many types of structures, such as automobile crush zones or blast doors, since it reduces the likelihood of occupant injury. However, lattice structures do not have inherently high penetration resistance since the structure is largely empty space. To improve penetration resistance, it is desirable to embed hard and/or strong, monolithic inserts into a lattice structure. 3D printed sand molds have been designed to allow the incorporation of monolithic ceramic and/or metal objects into the mold and, subsequently, these objects become embedded in the final metal casting.

***Keywords***: casting, lattice structure, ceramics, encapsulation, energy absorption

## 1 MULTI-FUNCTIONAL LATTICE STRUCTURES

There is a need for lightweight structures that can improve vehicle performance and safety while also decreasing vehicle transportation costs. To address this need, and other challenges associated with lightweighting structures, many have looked to cellular materials. Cellular materials can provide high strength, high stiffness, and high energy absorption, while maintaining low mass [1–3]. Due to the combination of low mass and high stiffness, cellular materials have found applications as filters, heat exchangers, biomedical prostheses, and blast resistant panels [3,4]. Various manufacturing techniques have been used to make cellular structures, resulting in both randomly oriented structures [5] and ordered structures [6].

While cellular materials and sandwich panels have been shown to be effective in mitigating blast loads, they do not meet all of the requirements for armor. Multi-functional material solutions are needed that offer low-mass plus protection from both blast and penetrators.

### 1.1 Additive Manufacturing of Metal/Ceramic (or Hard Metal) Composites

To provide designers with the ability to optimize both cellular topology and the location of encapsulated ceramics/hard metals, the authors have developed an Additive Manufacturing (AM) technique to produce metal/ceramic (or hard metal) composites. The layer by layer fabrication approach of the binder jetting AM processes provides the freedom to design the lattice structure to maximize structural performance [7] and the option of integrating monolithic embedded objects.

AM techniques have successfully produced complex topologies but powder-based approaches are limited in that they are only able to produce parts with a homogenous distribution of the matrix and ceramic materials and do not allow the designer to specify the location of the ceramic material. Also, the act of embedding an object (such as a ceramic tile) into a printed part is extremely difficult using powder bed AM techniques. While powder bed fusion AM processes have been successful in producing parts with cellular geometries, the available geometries are limited by process constraints [8].

### 1.2 Program Goal

The authors' goal was to develop an AM fabrication approach that gives the designer control over the lattice structure topology and allows for the embedding of ceramic or hard metal objects within the lattice structure [9-12]. Specifically, the authors have developed an AM manufacturing process in which binder jetting is used to print sand molds and cores for metal casting. The cores have a segmented design that allows the placement of ceramic or hard metal tiles that become encapsulated in metal during the casting operation, Figure 1.

This approach advances the state-of-the-art in metal/ceramic composite casting by creating lightweight lattice structure with strategically placed ceramic or hard metal tiles, which cannot be done with existing manufacturing technologies. This process has been used to produce cast metal lattice structures that can effectively dissipate blast energy and protect against penetration.

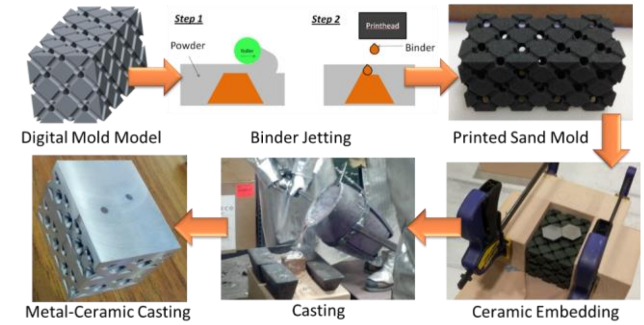



Figure 1: Overall process chain for producing metal-monolitic ceramic/hard metal composite castings using 3D printed sand molds and cores.

# 2 DEMONSTRATION

Various cast metal and tile combinations have been investigated (metals: Al-Cu alloy, Al-Si alloy, FeMnAl alloy; ceramics: boron carbide, aluminum oxide; hard metals: white cast iron). The iron-manganese-aluminum alloy (FeMnAl) had the best properties for this application.

Lattice strcutures have produced in both non-ferrous and ferrous alloys, including an aluminum copper alloy, nickel-aluminum-bronze, HY-80 steel, and FeMnAl alloy. The castings were 150mm x 150mm by 115 or 165mm tall (6”x6” by 4.5 or 6.5” tall), had 5mm (0.2”) diameter trusses, 6.35mm (0.25”) thick face sheets and had 63% open volume. 3-D printed sand molds (sleeves) and cores were used for casting these structures, Figure 2. The molds were designed to bottom fill to reduce turbulence and two downsprues were used to reduce temperature loss during mold filling.

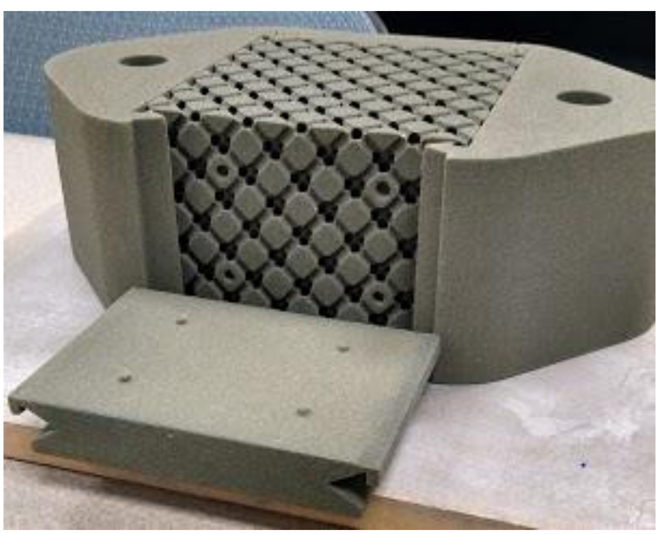


Figure 2: 3D printed sand mold (sleeve) and core for producing cast lattice structures. Pins in the sleeve sides hold the core securely in place during casting.

## 2.1 Encapsulation

Aluminum oxide tiles (6.35mm, 0.25” thick), boron carbide tiles (4mm, 0.16” & 9mm, 0.35” thick), and white cast iron tiles (4mm, 0.16” & 9mm, 0.35” thick) have been encapsulated in Al-Si, Al-Cu, and FeMnAl alloys. Three different encapsulation thicknesses have been evaluated: 3.2mm (0.125”), 4.8mm (0.188”) and 6.35mm (0.250”).

Visual and X-ray analysis showed that all encapsulations in Al-Si alloy were successful with no metal hot tearing or tile cracking, Figure 3. Tiles encapsulated in Al-Cu alloy showed mixed results.

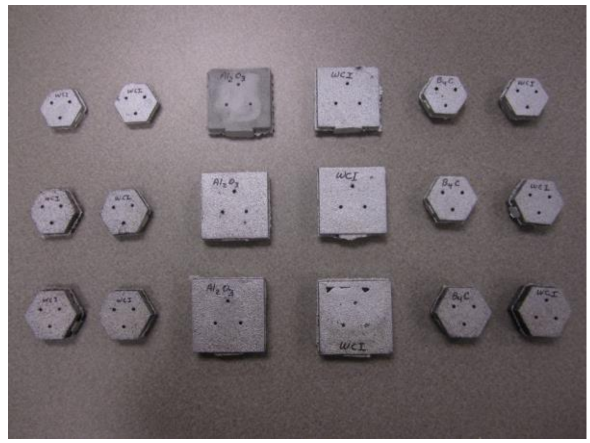
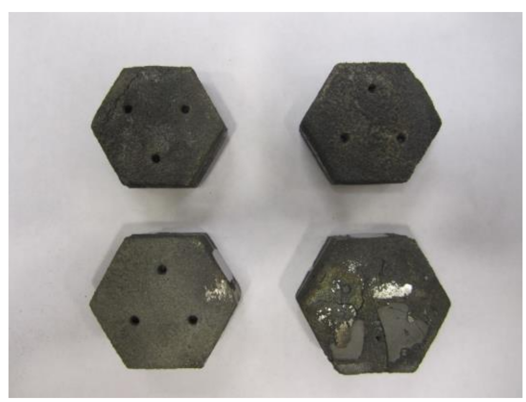


Figure 3: Examples of ceramic and hard metal tiles encapsulated in Al-Si alloy. The square tiles were 50mm x 50mm x 6.35mm thick.

Encapsulation in FeMnAl alloy was partially successful. Boron carbide tiles were either successfully encapsulated or exhibited cracking due to thermal shock. White cast iron tiles were either successfully encapsulated or exhibited hot tearing of the FeMnAl alloy, and aluminum oxide tiles fractured due to thermal shock. Examples of encapsulations in FeMnAl alloy are shown in Figure 4.



white cast iron tiles boron carbide tiles

Figure 4: Examples (good & bad) of tiles encapsulated in FeMnAl alloy.

## 2.2 Lattice Structure Castings

Lattice structure castings with and without ceramic/hard metal encapsulations have been successfully cast in aluminum-copper alloy, nickel-aluminum-bronze, HY-80 steel, and FeMnAl alloy, Figure 5.

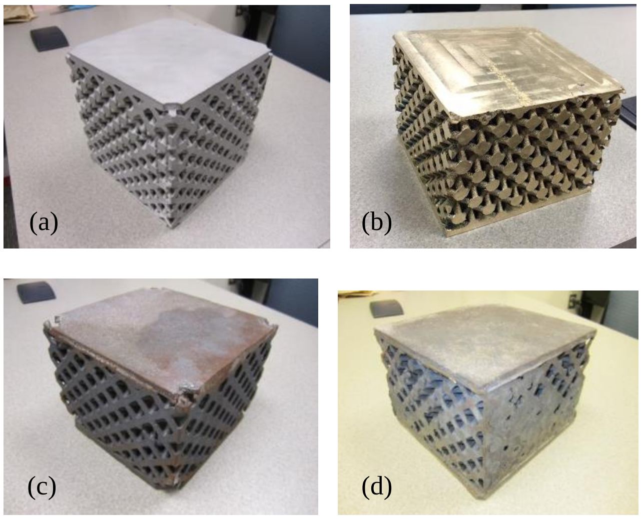
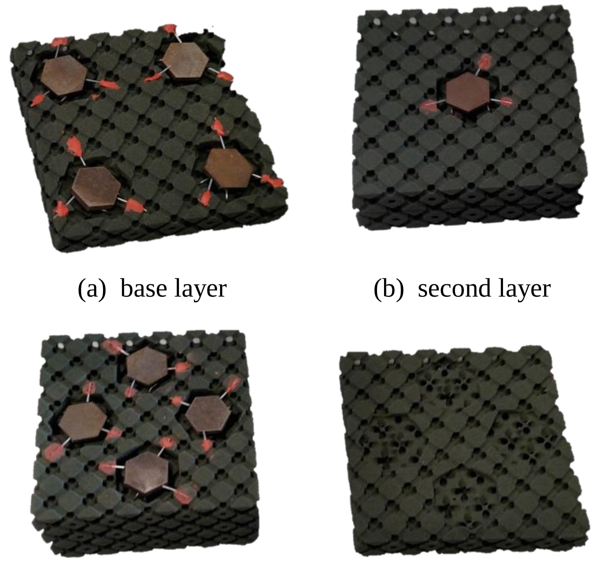



Figure 5: (a) aluminum-copper alloy, (b) nickel-aluminum-bronze, (c) HY 80 steel and (d) FeMnAl alloy lattice structure castings.

## 2.3 Metal/Hard Metal Composite Lattice Structure Castings

A 150x150x115mm FeMnAl metal/hard metal composite lattice structure with encapsulated white cast iron tiles was produced. The printed sand mold had four "core" layers, with space for tiles to be placed into each layer, Figure 6. The tiles were arranged to insure that a penetrator would hit at least one tile. The tiles were held in place with wire attached to the printed sand molds using core paste. The core layers were stacked and placed in a 3D printed sand sleeve (as shown previously in Figure 2). A pouring basin made from conventional bonded sand was placed on top of the printed sand assembly. A pouring basin with two downsprues and thin steel sheet covering the downsprues was used to insure that the pouring basin would be partially full before mold filling occurred to prevent the possibility of an interrupted pour. The chemistry of the FeMnAl alloy for this lattice structure was 31 wt% Mn, 4.2 wt% Al, 0.8 wt% Si, 0.9 wt% C, 0.5 wt% Mo. The final metal/hard metal composite lattice structure casting is shown in Figure 7.



(a) base layer (b) second layer

(c) third layer (d) top layer

Figure 6: 3D printed core layers for a producing a lattice structure with encapsulations.

Figure 7: A 150x150x115mm FeMnAl alloy composite lattice structure casting with white cast iron tile encapsulations.

## 2.4 Ballistic Testing

The FeMnAl alloy composite lattice structure casting with white cast iron tile encapsulations was shot with five 30.06 armor piercing rounds and three 50 caliber armor piercing rounds; none of these armor piercing rounds passed completely through the casting. The strike face and back face of the casting after being shot is shown in Figure 8.

strike face back face

Figure 8: Strike face and back face of FeMnAl alloy composite lattice structure casting with white cast iron tile encapsulations after being shot with 30.06 and 50 caliber armor piercing rounds. No rounds passed completely through the casting.

## 3 CONCLUSIONS

1. An Additive Manufacturing technique to produce metal/ceramic (or hard metal) composite castings has been developed that allows designers the ability to optimize both cellular topology and the location of encapsulated monolithic ceramic/hard metal objects.
2. Complex, lightweight, lattice structure castings with or without encapsulated tiles have been produced in both non-ferrous and ferrous metals using 3D printed sand molds and cores.
3. Monolithic ceramic and hard metal tiles have been encapsulated in both non-ferrous and ferrous metals using 3D printed sand molds and cores. Aluminum oxide, boron carbide and white cast iron tiles have been encapsulated in aluminum alloys. Boron carbide and white cast iron tiles have been encapsulated in FeMnAl alloy.
4. Complex lattice structure castings have been produced using gravity pouring without any special or unique casting processes or equipment.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the Virginia Tech graduate and undergraduate students that have contributed to this research effort over the past five years and express their sincere thanks to ExOne for providing the 3D printed sand molds & cores. The authors also wish to thank the students of the DREAMS (Design, Research and Education for Additive Manufacturing Systems) Lab and VT-FIRE (Virginia Tech Foundry Institute for Research and Education). The castings described in this report were produced at the Virginia Tech Kroehling Advanced Materials Foundry.

This material is based upon work supported by the National Science Foundation under Grant No. 1462089. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

1. Gibson, J. W., and Ashby, M. F., 1997, Cellular Solids: Structures and Properties, Cambridge University Press, Cambridge, UK.
2. Banhart, J., 2000, “Manufacturing Routes for Metallic Foams,” Memb. J. Miner. Met. Mater. Soc., 52 (December).
3. Degischer, H.-P., and Kriszt, B., 2002, Handbook of Cellular Metals: Production, Processing, Applications.
4. Thompson, S. C., Muchnick, H., Choi, H., and McDowell, D., 2006, “Robust Materials Design of Blast Resistant Panels,” Multidisciplinary Analysis and Optimization Conference, pp. 1–15.
5. Banhart, J. and D. Weaire, 2002, "On the Road Again: Metal Foams Find Favor," *Physics Today*, July, pp. 37-42.
6. Wadley, H. N. G., N. A. Fleck and A. Evans, 2003, "Fabrication and Structural Performance of Periodic Cellular Metal Sandwich Structures," *Composites Science and Technology*, Vol. 63, pp. 2331-2343.
7. Evans, A. G., J. W. Hutchinson, N. A. Fleck, M. F. Ashby and H. N. G. Wadley, 2001, "The Topological Design of Multifunctional Cellular Metals," *Progress in Material Science*, Vol. 46, pp. 309-327.
8. C. B. Williams, F. Mistree, D. W. Rosen, 2005, “Investigation of Additive Manufacturing Processes for the Manufacture of Parts with Designed Mesostructure,” ASME IDETC 10th Design for Manufacturing and the Life Cycle Conference, September 24-28, Long Beach, CA, Paper No. DETC2005/DFMLC-84832.
9. D. Snelling, C. B. Williams, C. Suichital, A. Druschitz, 2015, “Fabrication of Cordierite Preforms via Binder Jetting,” International Solid Freeform Fabrication Symposium, Austin, TX.
10. D. Snelling, Q. Li, N. Meisel, C. B. Williams, R. C. Batra, and A. P. Druschitz, “Lightweight Metal Cellular Structures Fabricated via 3D Printing of Sand Cast Molds,” Advanced Engineering Materials, published online March 11, 2015 (DOI: 10.1002/adem.201400524.
11. Popernack, Allison. “Cast Aluminum Mesostructures Using 3D Printed Sand Cores with an Encapsulation.” *International Journal of Metalcasting*, vol. 10, pp.111-113, Jan. 2016.
12. A.P. Druschitz, S. Cowden, A. Dudley, S. Walsh, A. Weir, C.B. Williams, B. Wood, “Metal-ceramic composite lattice structures using 3D printed sand molds and cores,” International Solid Freeform Fabrication Symposium Proceedings, Austin, TX (2016).