Video Article

Indirect Fabrication of Lattice Metals with Thin Sections Using Centrifugal Casting

Jiwon Mun[1], Jaehyung Ju[1], James Thurman[2]

[1]Department of Mechanical and Energy Engineering, University of North Texas

[2]Department of Studio Art, University of North Texas

Correspondence to: Jaehyung Ju at jaehyung.ju@unt.edu

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Abstract

One of the typical methods to manufacture 3D lattice metals is the direct-metal additive manufacturing (AM) process such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM). In spite of its potential processing capability, the direct AM method has several disadvantages such as high cost, poor surface finish of final products, limitation in material selection, high thermal stress, and anisotropic properties of parts. We propose a cost-effective method to manufacture 3D lattice metals. The objective of this study is to provide a detailed protocol on fabrication of 3D lattice metals having a complex shape and a thin wall thickness; *e.g.*, octet truss made of Al and Cu alloys having a unit cell length of 5 mm and a cell wall thickness of 0.5 mm. An overall experimental procedure is divided into eight sections: (a) 3D printing of sacrificial patterns (b) melt-out of support materials (c) removal of residue of support materials (d) pattern assembly (e) investment (f) burn-out of sacrificial patterns (g) centrifugal casting (h) post-processing for final products. The suggested indirect AM technique provides the potential to manufacture ultra-lightweight lattice metals; *e.g.*, lattice structures with Al alloys. It appears that the process parameters should be properly controlled depending on materials and lattice geometry, observing the final products of octet truss metals by the indirect AM technique.

Video Link

The video component of this article can be found at https://www.jove.com/video/53605/

Introduction

Cellular metals are the metals made up of an interconnected network of solid struts or plates and have complex micro-architectures with voids[1]. Examples include both i) randomly structured stochastic foams and ii) periodically ordered two-dimensional (2D) honeycombs and three-dimensional (3D) lattice truss structures. They have received attention due to their high specific stiffness and strength[1-3]and high specific resilience[4-5], excellent energy absorption for impact loading[6], acoustic insulation[7], possible design of heat dissipaters and heat exchangers[8]. Especially, periodically ordered lattice structures have the potential to engineer the properties superior with a capability to control the internal porous network geometry.

Due to their complex internal porous network geometry, it is difficult to manufacture cellular metals using the conventional subtractive machining. As such, researchers have started looking for alternative methods to fabricate cellular metals: forming gas in liquid metal or mixing metal powder with blowing agents were explored for manufacturing stochastic metal forms[9]. Due to the lack of control over cell topology, it is hard to tailor mechanical properties. Alternatively, manufacturing methods for periodically ordered cellular metals were explored: stamping thin sheets of metal into a corrugated shape followed by joining them to create periodic structures[10], bonding slotted metal sheets[11], extrusion[12], weaving and blazing metal filaments to fabricate textiles[13]. Even though these manufacturing methods offer repeatable patterns, the patterns are still limited in the planar direction. In an effort to generate 3D pattern repetition, researchers started using additive manufacturing (AM); *e.g.*, Selective Laser Melting (SLM)[14], Electron Beam Melting (EBM)[15], and Direct-Metal Laser Sintering (DMLS)[16]. Despite their capability to fabricate 3D ordered complex lattice geometries, there still exist some limitations: difficulty using metals with high thermal conductivity and high optical reflectivity[17], high thermal residual stress[18], poor surface finish with the 'balling' phenomenon during laser or electron melting [19], anisotropic properties[20-21] of parts caused by a combined effect of the layered manufacturing, anisotropic formation of grains, powder size, power and scanning speed of laser or electron beam[15], high energy consumption, *etc*.

Combining polymer based AM with metal casting may provide an alternative method to manufacture lattice metals. One may call this "indirect AM". Indirect AM may provide a solution to overcome the technical problems of direct AM of metals mentioned above. Several efforts have been made to manufacture lattice metals using indirect AM combining 3D printing of polymers with gravity based casting[22-25]; *e.g.*, an investment casting combined with fused deposition modeling (FDM) to fabricate a lattice alloy[22-25] or sand casting combined with a sand powder based AM[23]. The gravity based casting appears to remain a technical challenge to overcome - misrun and porosity caused by sudden solidification of molten metals when they meet network structures with sharp corners of lattice structural molds[25-26]. Relatively large surface area of lattice structural molds also appears to contribute to sudden cooling, resulting in premature solidification[25-26].

In this study, we propose an alternative indirect AM that may overcome the misrun during manufacturing of lattice metals - centrifugal casting to a lattice mold cavity made by a 3D printed lattice sacrificial polymer pattern. We use a digital light processing (DLP) based 3D printing method to build a lattice structural sacrificial pattern followed by centrifugal casting of Al and Cu alloys. The objective of this study is to provide a detailed protocol on fabrication of 3D lattice metals having a complex shape and a thin wall thickness. The main contribution of this process is to provide an opportunity to extend the selection of materials with low manufacturing cost for manufacturing lattice metals.

Protocol

1. Planning of Experiment

1. Draw a sacrificial pattern (an octet truss structure with a sprue system) using computer aided design (CAD) software as shown in **Figure 1** and save the CAD model as an STL file format.
   Note: The sacrificial pattern is an integrated pattern of the octet truss structure with a sprue system that will be eventually melted for casting. Because the sacrificial pattern includes both the octet truss structure and the sprue system, it does not exactly represent the octet truss itself. A STL file of the sacrificial pattern is provided. Record the volume of the sacrificial pattern provided by CAD software, which will be used for calculating metals' mass.
2. Open the CAD drawing of the sacrificial pattern on the 3D printing software connected to a 3D printer for printing the pattern.
3. Ensure that the 3D printer has enough UV curable/castable acrylic plastic and a support material made of a wax in the printer cartridges.

2. Fabrication of Sacrificial Pattern

1. Manufacture the sacrificial pattern consisting of the octet truss structure and the sprue system using a 3D printer (**Figure 2A - C**).
   Note: Processes in 2.1.3 - 2.1.7 are not required if a 3D printer which does not generate supporting materials is used.
   1. Send an STL file of the sacrificial pattern to the 3D printer to print a sacrificial pattern (**Figure 2A**).
   2. Melt out a support material of the sacrificial pattern in an oven at above the melting temperature of the support material (60 - 70 ℃) for 2 hr (**Figure 2B**).
      Note: The temperature to remove the support material should not be too high. Otherwise, it may cause damage to the sacrificial pattern. The sacrificial pattern starts getting damaged at around 80 ℃ in this study.
      Note: The melting temperature of support materials varies with 3D printers where different support materials may be used.
   3. Fill out a digital ultrasonic cleaner with baby oil up to 2.5 L, the maximum volume that the cleaner can contain (**Figure 2C**).
      Note: It was recommended by the supplier of the 3D printer to use baby oil for dissolving residue of the wax-like support material.
   4. Put the sacrificial pattern into the digital ultrasonic cleaner and turn on the power of the cleaner (**Figure 2C**). Make sure that the sacrificial pattern is fully submerged in the oil.
   5. Remove residue of the support material by dipping the sacrificial pattern into the oil at 65 ℃ for 40 min (**Figure 2C**).
   6. Take out the sacrificial pattern from the cleaner if the support material is completely removed.
   7. Have the sacrificial pattern dry with a fan at RT (~20 ℃) (**Figure 2C**).
      Note: It takes about 2 hr until the oil on the surface of the sacrificial pattern is fully dried. Consider the sacrificial pattern to be fully dried if the surface is not sticky.

3. Fabrication of Mold

1. **Pattern Assembly**
   1. Attach a rubber gasket to the sacrificial pattern (the octet truss with the sprue system) and place them on the bottom of a cylinder-shaped flask with a height of 6.35 cm and a diameter of 6.35 cm (**Figure 2D**).
      Note: Prepare two flasks for casting each metal; Al and Cu alloys.
   2. Double check the rubber gasket with the sacrificial pattern is completely attached to the bottom of the flask.
   3. Wrap the flask with a duct tape so that investment powder-water mixture, whose procedure will be described in the next section, may not leak from the flask.

2. **Preparation of Investment Mold**
   1. Prepare investment powder ($CaSO_4$, ρ = 1019 kg/m^3) of 89 g, which is 87.16 ml. Use a scale for weighing the investment powder.
      Note: The physical properties of the investment powder are shown in **Table 1**.
   2. Pour the investment powder into a mixing bowl (1 L).
   3. Pour water (114 ml) into the mixing bowl. Use a beaker to measure the volume of water.
   4. Mix the investment powder with water in the bowl for 3 min. Mix well until there are no lumps in the investment powder-water mixture. Otherwise, it may cause poor surface quality of investment mold. Follow the work-flow, as shown in **Figure 3**.
   5. In order to remove air bubbles in the mixture, place the bowl in a vacuum chamber for 90 sec until the air bubbles cannot be seen in the mixture with bare eyes (**Figure 3**).
   6. Pour the mixture into a flask embedding the sacrificial pattern and the rubber gasket (**Figure 2E**).
   7. Place the flask in the vacuum chamber again for 90 sec to remove the residue of air bubbles inside the mixture **(Figure 3)**.
   8. Dry the mixture inside the flask until it is hardened at RT (**Figure 3**).
      Note: Usually, it takes about 10 - 15 min for the mixture to be hardened at RT.
   9. Remove the flask and the rubber gasket at the bottom of the mixture in the flask once the mixture is hardened (**Figure 3**). This product may be called a plaster mold.

3. **Burn-out**

1. Set up a burn-out time in a furnace while following the heating and cooling schedule (**Figure 4**) heating from 23 to 150 °C at 2.1 ℃/min; 150 to 370 ℃ at 3.7 ℃/min; 370 to 480 ℃ at 1.85 ℃/min; 480 to 730 ℃ at 4.17 ℃ /min; 730 ℃ for 1 hr; cooling 730 to 480 ℃ at -4.17 ℃ /min.
   Note: The time for burn-out varies with size of a flask. In this study, set the burn-out time to 6 hr.
2. Place the plaster mold in a furnace (**Figure 2F**).
3. Turn on the furnace and increase temperature in the furnace to remove the sacrificial pattern inside the plaster mold. Follow the temperature condition in **Figure 4**.
   Note: Because the UV curable/castable acrylic plastic, the materials of the sacrificial pattern, is a thermosetting acrylic-polymer plastic, it does not flow but is dissociated to a gas phase in the furnace.

4. **Centrifugal Casting** (**Figure 2G**)
   1. Check that the centrifugal casting machine's arm spins with an angular velocity of 425 rpm using a tachometer after turning on the power of a centrifugal casting machine.
   2. Prepare two ceramic crucibles that can hold a 150 g alloy to melt. Use separate crucibles for Al and Cu alloys to keep them from being contaminated with each other.
   3. Turn on the power of the centrifugal casting machine.
   4. Using a metal cutter, chop the alloys into pieces with 10 - 20 mm in length. Prepare them enough to fully fill the mold cavity whose volume should be the same as the sacrificial pattern.
      Note: The mass of metals necessary to fill out the same volume of the mold cavity varies considering varying density for each metal.
   5. Wear flame retardant cloths and gloves, and goggles. Prepare a bucket of water (30 L) at RT.
   6. Take the plaster mold temporarily out from the furnace in Section 3.3, install it in the flask cradle and balance the arm of the centrifugal casting machine (**Figure 5**).
   7. Place the plaster mold back to the furnace and pre-heat up to 482 °C before casting.
   8. Place the crucible in the crucible holder (**Figure 5**).
   9. Put the chopped alloy into the crucible.
   10. Open the valve of an oxygen tank connected with an oxygen-acetylene torch and maintain a pressure level in the tank of 96.5 kPa (14 psi).
   11. Ignite the oxygen-acetylene torch with a lighter and control the intensity of the flame by adjusting the mix of gases.
       Note: Caution is needed when using the oxygen-acetylene torch. Its maximum temperature of the torch is around 1,200 °C.
   12. Melt chopped alloy (Al alloy or Cu alloy) with the torch in the crucible until the alloy completely becomes liquid.
   13. Stir the alloy in the crucible with a carbon rod until the chopped alloy is completely melted.
   14. Place the plaster mold in the flask cradle back next to the crucible containing molten alloy (**Figure 5**).
   15. Close the cover of the centrifugal casting machine, let the centrifugal arm rotate and wait at least for 3 min.
       Note: The centrifugal casting machine starts operating as soon as the cover of the casting machine is closed. The centrifugal arm rotates at a speed of 425 rpm which corresponds to the inlet velocity at the mold cavity of the sacrificial pattern, v_r = 8.03 m/sec[28, 29] in **Figure 5** where the inlet-velocity is calculated using the macroscopic particle dynamics from an angular velocity of the centrifugal casting arm[28, 29].
   16. Turn off the power of the centrifugal casting machine after the 3 min rotation of the arm.
   17. Open the cover of the casting machine.
   18. Take the plaster mold out of the flask cradle using tongs.
   19. Keep the mold at RT for 15 - 20 min until the color of molten alloy turns to its original one in the solid phase.
   20. Using tongs, quench the plaster mold in water placed in a bucket (30 L) at RT for about 5 min. Make sure that the temperature of the plaster mold is close to RT after quenching.
   21. In order to obtain the lattice metal inside the mold, dissolve the mold in water. The mold made of gypsum dissolves easily in water.

4. Post Processing for Final Products of Octet Truss Metals

1. Turn on the power of a sandblaster.
2. Place the octet truss metals on the platform inside the sandblaster and close the door of the machine.
3. Put on gloves and grab the sandblaster pistol.
4. Grab the sprue part of the metal product and blow out the residual plaster from the lattice metal with the sandblaster for 2 hr.
   Note: The intensity of the sandblaster is automatically fixed approximately at 550 kPa. Once the sandblaster is operated, then the air comes out automatically from the pistol.
5. Keep the sandblaster running until the investment plaster residue inside the octet truss metal is completely removed while checking with the naked eye.
   Note: There is not a microscopic criterion on removal of plaster residue. This is beyond the scope of this study. The removal of the plaster residue is easily determined with the naked eye. Because the octet truss is an open cell structure, it is possible to see through and check if whether or not the plaster residue is completely removed.
   Note: Caution is needed for the sandblaster to not damage the octet truss metal with a thin wall thickness (0.5 mm) at the high pressure (550 kPa).
6. If the investment plaster residue inside the octet truss metal is not fully removed with the sandblaster, use additional post processing methods; *e.g.*, an ultrasonic cleaning or leaving the product in water for a day.
7. In case of using an ultrasonic cleaner, fill 0.7 L water into the ultrasonic cleaner and place the octet truss metal with plaster residue in the ultrasonic cleaner.
   1. Turn on the power of the ultrasonic cleaner.
   2. Set an operation condition; *e.g.,* 3 hr at 70 °C.
   3. Take the octet truss metal out of the ultrasonic cleaner once the operation ends.

4. Dry the octet truss metal at RT until water on the metal surface is completely removed.

8. As an alternative post processing method, leave the octet truss metal in water. This causes the plaster residue to be dissolved in water.
    1. Place the octet truss metal with the plaster residue in water and leave it for one day so that the bonding force between the investment plaster and the metal surface becomes weaken in water.
    2. Take the octet truss metal out of water.
    3. Dry the octet truss metal at RT until water on the metal surface is completely removed.

9. Using a saw or other proper tools, cut the metal filled the cavity of the sprue system part out of the metal product and obtain the final octet truss metal with a size of 25 mm x 25 mm x 25 mm, as shown in **Figure 1B**.

Representative Results

Using the indirect additive manufacturing described in the protocol section, Al and Cu alloys were used for manufacturing octet truss metals, as shown in **Figure 1**. The whole casting procedure is summarized in **Figure 2**. The procedure consists of eight sections: (a) sacrificial pattern printing (b) melting-out of support material (c) removal of residue of support material (d) pattern assembly (e) investment (f) burn-out of sacrificial patterns (g) centrifugal casting, and (h) post-processing. The investment mixing process was performed in order to make sure that there were no lumps in the investment-water mixture, as shown in **Figure 3**. The burn-out process was carried out for 6 hr to melt out the sacrificial pattern as shown in **Figure 4**, followed by the centrifugal casting process (**Figure 2G** and **Figure 5**). **Figure 6** shows the final products of octet truss metals with Al and Cu alloys. It shows that the molten Al alloy fully fills the entire lattice mold cavity without misrun. On the other hand, the molten Cu alloy appears to have a casting defect with premature solidification at the early stage of injection of molten metal at the inlet.

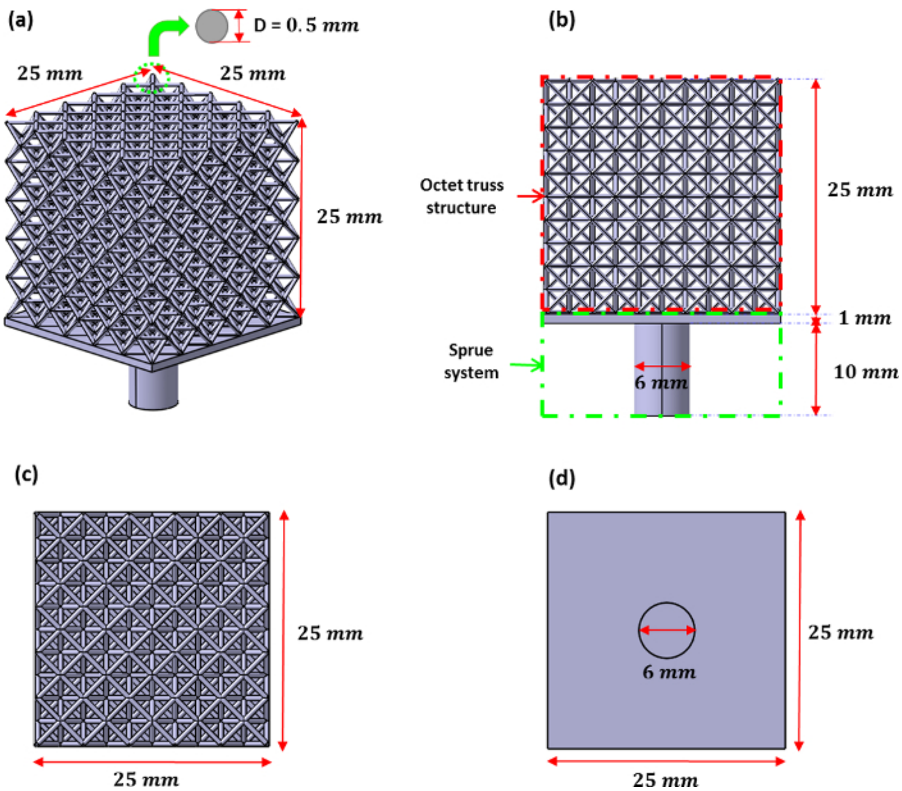

Figure 1. A Schematic of Octet Truss Structure with a Sprue System. Figure 1 shows a schematic of a sacrificial pattern of octet truss structure with a sprue system used in this study. The sprue system consists of a sheet of a 1 mm thickness, a 25 mm width, and a pillar having 10 mm in height and 6 mm in diameter. The sprue system can be modified using CAD software, if needed, for design of better fluidity of liquid metal. Please click here to view a larger version of this figure.

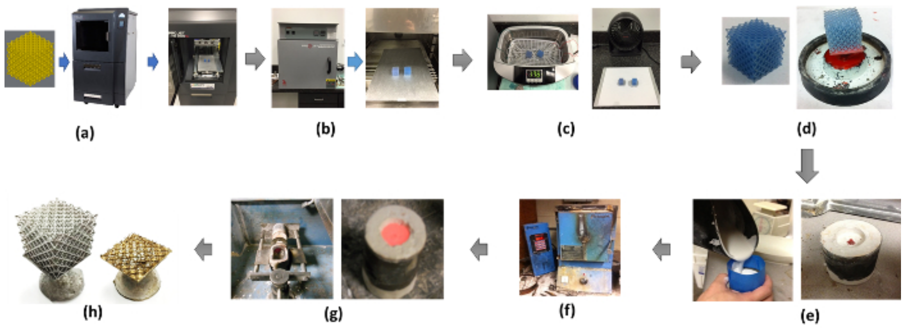

Figure 2. An Overview of the Indirect AM with Centrifugal Casting Procedure: (**A**) pattern printing (**B**) melt-out of support material (**C**) removal of residue of support material (**D**) pattern assembly (**E**) investment (**F**) burn-out of sacrificial pattern (**G**) centrifugal casting, and (**H**) post processing. This figure shows the whole procedure on fabricating octet truss metals using indirect AM with centrifugal casting. Please click here to view a larger version of this figure.

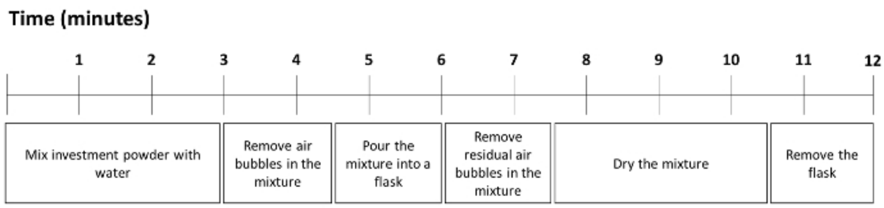

Figure 3. Work Schedule on Preparation of the Plaster Mold. Figure 3 shows the preparation of the plaster mold and the procedure to harden it in the flask. Please click here to view a larger version of this figure.

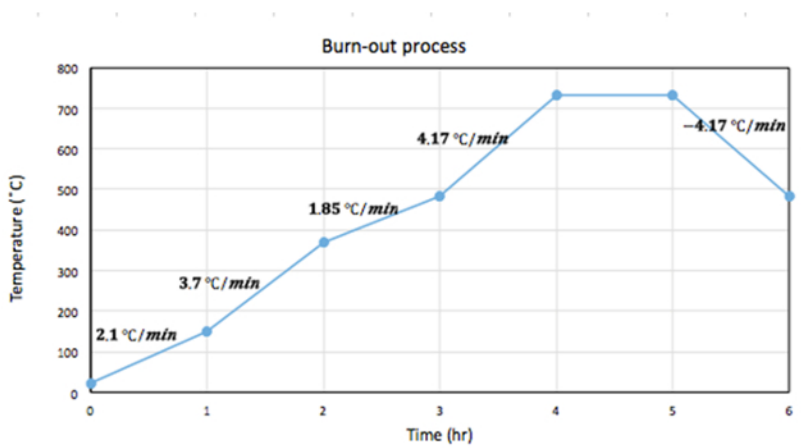

Figure 4. Burn-out Schedule of Sacrificial Pattern Inside the Plaster Mold. Figure 4 shows the burn-out process of the sacrificial pattern inside the hardened mixture. Please click here to view a larger version of this figure.

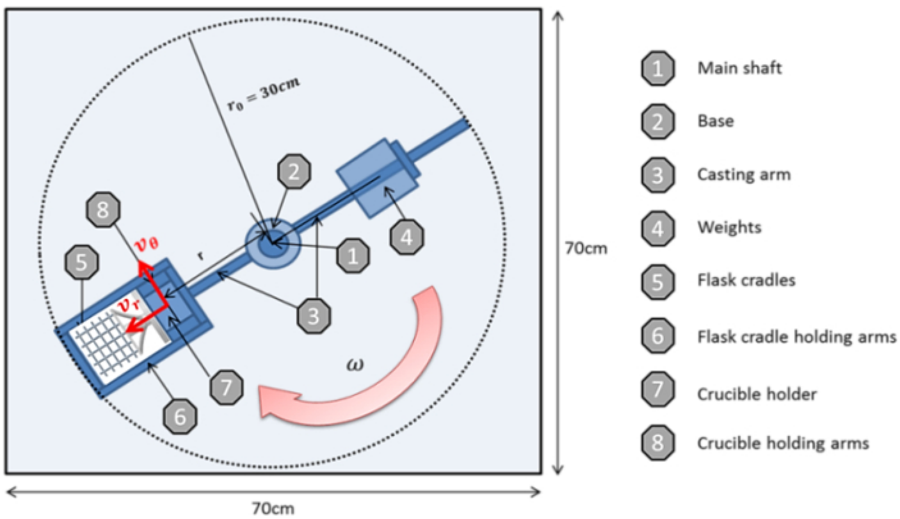

Figure 5. A Schematic of a Centrifugal Casting Machine. The centrifugal casting machine consists of eight components: main shaft, base, casting arm, weights, flask cradles, flask cradles holding arms, crucible holder, and crucible holding arms. The casing arm is balanced with moving weights along the casting arm. Please click here to view a larger version of this figure.

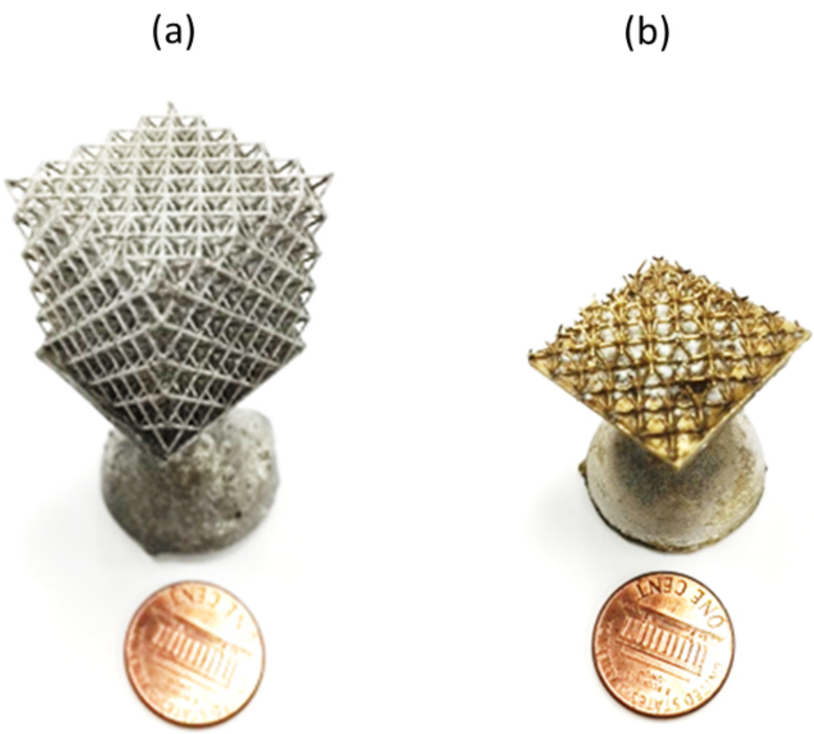

Figure 6. Final Product of Octet Truss Metals: Octet truss structures with (**A**) Al and (**B**) Cu alloys. It shows a fairly good degree of completion on the octet truss Al alloy. On the other hand, a poor degree of completion is observed with the octet truss Cu alloy. Please click here to view a larger version of this figure.

Property	**Value [unit]**
Density at 20 °C	1,019 [kg/m^3]
Thermal conductivity at 20 °C	0.47 [W/(m*K)]
Thermal expansion coefficient at 20 °C	7.22E-6 [/°C]
Roughness	2.72E-6 [m]

Table 1. **Properties of the Investment Powder.** This table shows the physical properties of the investment powder used in this study.

40 ml water to 100 g powder							
Flask diameter	Height						
	5.08 cm	6.35 cm	7.62 cm	8.89 cm	10.16 cm	12.7 cm	15.24 cm
6.35 cm	226.8 g 91 ml	283.5 g 114 ml	340.19 g 136 ml	396.89 g 160 ml	453.59 g 183 ml	566.99 g 228 ml	
(Top figure - Investment powder (g), Bottom figure - Water (ml))							
Note: In this study, a flask with a height of 6.35 cm and a diameter of 6.35 cm is used.							

Table 2. Mixing Conditions of Investment Powder with Water for a Varying Flask Size: This table shows the mixing conditions of the investment powder and water for a varying flask size recommended by manufacturer. In this study, a flask with a height of 6.35 cm and a diameter of 6.35 cm is used.

(a) Chemical composition of Al alloy			
Material	Unit		
Aluminum alloy	Chemical composition		
		Al	Cr
	Min./Max.	>99	<0.05
(b) Physical properties of Al alloy			
Property		Unit	
Liquidus temperature		660 °C	
Solidus temperature		660 °C	
Density		2,340[kg/m^3] @850 °C	
Specific heat		1,090 J/kg·°C	
Thermal conductivity		0.9428 [W/(cm*°C)] @850 °C	
Viscosity		0.00087 [Pa·s] @850 °C	
Surface tension coefficient		900 [N/mm]	

Table 3. **Chemical Composition and Physical Properties of Al Alloy[30]:** (a) Chemical composition of Al alloy and (b) Physical properties of Al alloy.

(a) Chemical composition of Cu alloy						
Material	Unit					
Copper alloy (Jewelry bronze)	Chemical Composition (%Max, unless shown as range of mean)					
		Cu	Si	Zn	Mg	Pb
	Min./Max.	91.9	4	4	0.25 Max	0.25 Max
(b) Physical properties of Cu alloy						
Property			Unit			
Liquidus temperature			1,035 °C			
Solidus temperature			1,005 °C			
Density			7,200 [kg/m^3] @1200 °C			
Specific heat			380 J/kg·°C			
Thermal conductivity			1.44 [W/(cm*#)] @1200 °C			
Viscosity			0.0038[Pa·s] @1200 °C			
Surface tension coefficient			1,500 [N/mm]			

Table 4. **Chemical Composition and Physical Properties of Cu Alloy[30]:** (a) Chemical composition of Cu alloy and (b) Physical properties of Cu alloy.

Discussion

For conventional metal casting, it is important to keep the molten metal's flow smooth and streamlined in 'laminar' in the mold cavity and rather avoid irregular and agitated flow generally observed in turbulent flow[27]. Accordingly, it is important to properly design the inlet of the sprue system associated with the rotating speed of a centrifugal arm to maintain the flow of molten metal inside the lattice mold cavity 'laminar'.

In this study, the critical steps of the protocol are the mixing of investment powder with water, the burn-out of sacrificial pattern, and the centrifugal casting process. The mixing process of investment powder with water is important because quality of the plaster mold is mainly controlled by this process, subsequently influencing the degree of completion of the final products of octet truss metals. For instance, if the investment-water mixture is too coarse, the surface roughness becomes high, resulting in poor surface finish of final products. The burn-out process of the sacrificial pattern is also essential to determine the quality of final products because residue of the sacrificial pattern causes a casting defect such as misrun or metal penetration if the sacrificial pattern is not completely burned out. The last key step is the centrifugal casting process. Proper setup for casting is required to fully fill liquid metal out in the investment mold cavity with a complex network shaped octet truss structure.

As can be seen in **Figure 6**, under the same processing conditions, *e.g.*, the inlet velocity, the inlet temperature of molten metal, pre-heat temperature of mold, Cu alloy shows a premature solidification in a lattice mold cavity with a wall thickness of 0.5 mm (**Figure 6 (b)**). This is thought be caused by the high surface tension (1,500 N/mm) and high viscosity (0.00038 Pa·s) of Cu alloy through the micro-channel in the lattice mold cavity. On the other hand, it appears that a relatively low surface tension coefficient (900 N/mm) and viscosity (0.00087 Pa·s) of the molten Al alloy enables it to fully fill the octet truss lattice mold cavity. It is recommended to find an optimum inlet velocity of molten metal for casting 3D network lattice structures with a thin wall thickness in order to overcome the sudden change in flow-direction of molten metal and the effect of surface tension in the micro-channel of the lattice structural mold cavity.

The surface tension effect of molten metal is known to be dominant at a thin channel where this lattice cavity mold geometry in this study can be applied. It may be possible to manufacture a lattice Cu alloy with a thicker wall thickness and higher injection velocity of centrifugal casting as demonstrated in our previous work [28-29].

Direct AM methods such as SLM and EBM have been considered for possible manufacturing methods for lightweight 3D lattice metals. However, direct AM methods appear to be limited in selecting materials. For example, current EBM technology is limited to Ti-6Al-4V and Inconel[31]. In spite of its extensive use in aerospace and bio-implant applications, aluminum, for example, is not being produced using this technology. Theoretically, it could be possible to extend the direct AM to other powder metals through close control of process parameters. However, practically, the direct AM has been reported to have difficulty in fabricating parts with metal powders with high optical reflectance and high thermal conductivity, *e.g.*, Al. Moreover, evaporation and possible explosion inside the build chamber have been issued for aluminum powder[31].

The proposed indirect AM technique is significant because this enables to manufacture lattice structures with metals where direct AM methods experience difficulty, resulting in empowering overall manufacturing capability of 3D lattice metals with both direct and indirect AMs by expanding the range of selection of metals. In addition, centrifugal casting, a step in this study, is known to provide an isotropic property of metal parts due to relatively equal spread of molten metal into the mold cavity. This may resolve the current issue of direct AM on anisotropy caused by both layered manufacturing and anisotropic formation of grains[20-21].

Exploring other metals for indirect AM together with studies on the effect of process parameters on lattice geometries will be left to our future work.

Disclosures

The authors have nothing to disclose.

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