Selective Separation Sintering (SSS) A New Layer Based Additive Manufacturing Approach for Metals and Ceramics

Jing Zhang, Behrokh Khoshnevis

University of Southern California, Department of Industrial and Systems Engineering
Los Angeles, CA, 90089

Abstract

Selective Separation Sintering (SSS) is a powder layer based Additive Manufacturing approach. SSS can fabricate high temperature ceramic and metallic parts at comparatively lower cost with high quality. In the printing process a dry powder of higher sintering temperature is deposited into the base material which makes up the part. The inserted powder defines the boundary of the part and separates the part from its surroundings. When printing of all layers is completed the deposited dry powder serves as a separation coating which defines the shape of the part. In the sintering process the base material is sintered into a solid part while the separation coating remains as loose powder. The part is then separated from the surrounding area at the separation coating surfaces, and is post processed if necessary. Preliminary results have proven the capability of SSS in successfully printing ceramic and metallic parts. Future experiments are planned for improving the process resolution.

Keywords: Selective Separation Sintering (SSS); Additive Manufacturing (AM); Ceramics; Metal

1. Introduction

The commercially available AM technologies for fabricating metallic parts employ high power density beams or apply binder with post sintering. To date, selective laser/electron beam melting (SLM & EBM) are most often used AM methods to produce near full density metallic parts of high resolution. Due to high up-front investment (~$1 million) and expensive operating and maintenance cost, SLM and EBM are mainly used by big corporations or institutes like NASA, GE, hospitals and universities[1]. In cases where full density is not required or infiltration is acceptable, a relatively low cost approach like sintering is more appropriate. Selective laser sintering (SLS) has similar hardware and operating environment requirements as that of SLM which makes SLS also a high cost approach [1]. Green parts bonded by binder with post sintering by ExOne is capable of manufacturing metallic parts at relatively low cost but the binder also contaminates the parts [2]. The binder approach has problems to process materials sensitive to contamination such as titanium alloys [3]. Selective inhibition sintering (SIS) takes an opposite of ExOne binder approach by inhibiting the boundary of the part during sintering, providing an economic solution for making certain metals, including bronze. The applicability of SIS in more metallic materials is still under investigation [4].

There are few commercially available technologies that can produce functional ceramic parts. Electron beam melting cannot be applied to ceramics due to the fact that most ceramics are electrically non-conductive. Laser beam melting of ceramics faces the problem of cracks formation as a result of large thermal stress [5]. Efforts to preheat the powder bed to high temperature (e.g. 1600 °C) can avoid cracks formation but long time preheating may cause rough edge due to solid phase sintering of non-part powder [6]. Binder based technologies do

[1] http://www.arcam.com/solutions/creating-value-additive-manufacturing/

not have the problem of cracks formation during printing. While in the pyrolysis stage, the space previously occupied by the binder is released and large shrinkage rate is to be expected. Currently, binder based 3D printing of ceramics is mainly used on concept design [7].

Under such context, SSS (Selective Separation Sintering) is developed to print functional parts at relatively low cost with high quality for a variety of materials including ceramics [8], metals, etc.

2. Operating Principles of SSS

In the SSS process, two kinds of powders are used, the base powder (B-powder), which makes up the final part, and the separator powder (S-powder) which isolates the part from the surrounding B-powder region. The S-powder is selectively deposited into the B-powder layer, forming a barrier surrounding the loose powder that eventually becomes the part. The printed green part is moved into a furnace for bulk sintering. After sintering, the S-powder coating remains loose and unsintered, making the part easily removable.

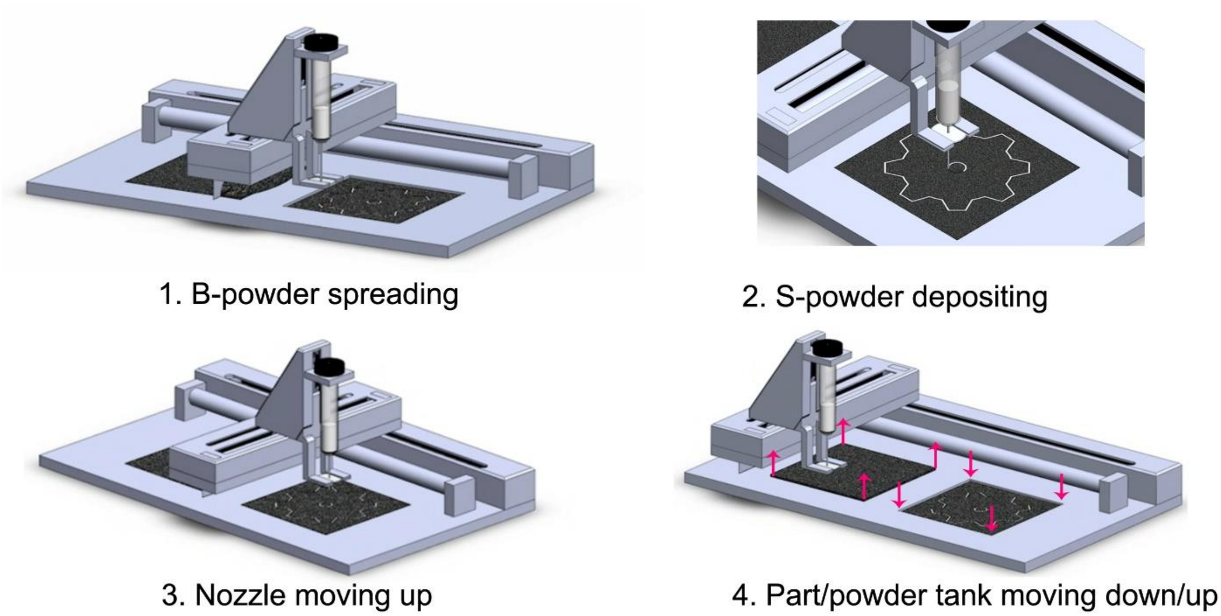


Figure 1. Printing process of SSS. 1. B-powder spread; 2. S-powder deposition; 3. Nozzle raised; 4. Part tank lowered, powder tank raised

The SSS process can be described by the following steps as illustrated in Figure 1:

1. A thin layer of B-powder is spread over the part tank;
2. The S-powder deposition nozzle is lowered into the B-powder layer, selectively depositing the S-powder at the layer boundary;
3. The nozzle is raised to provide clearance for subsequent movement;
4. Raise up the B-powder storage tank and lower the platform for one layer thickness;
5. Steps 1-4 are repeated until all layers are completed;
6. The green part is moved to a sintering furnace.
7. The sintered part is removed from the furnace. The surrounding material is easily removed revealing the final part.

Successful separation of the part is dependent on the difference in sintering temperature between the S-powder and the B-powder. As illustrated in Figure 2, the green piece in the furnace is heated up following a chosen sintering profile. The actual sintering temperature (blue) is carefully chosen so that it is higher than the sintering temperature of B-powder (green), but not high enough to sinter the S-powder (red). As a result, the B-powder becomes well sintered, while the S-powder remains loose.

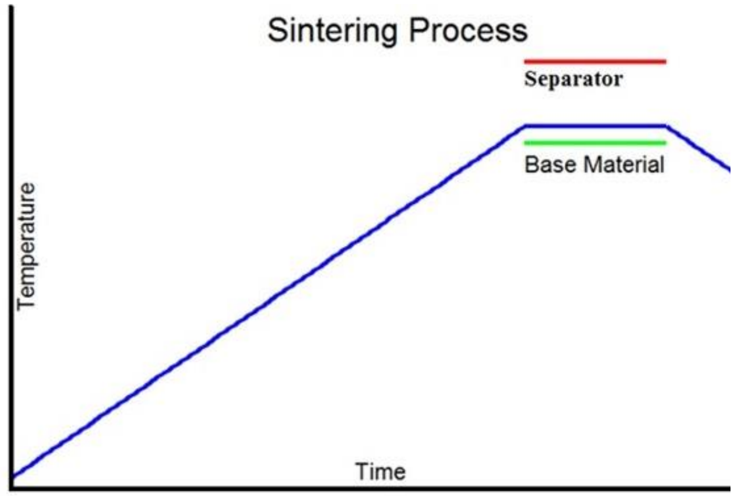
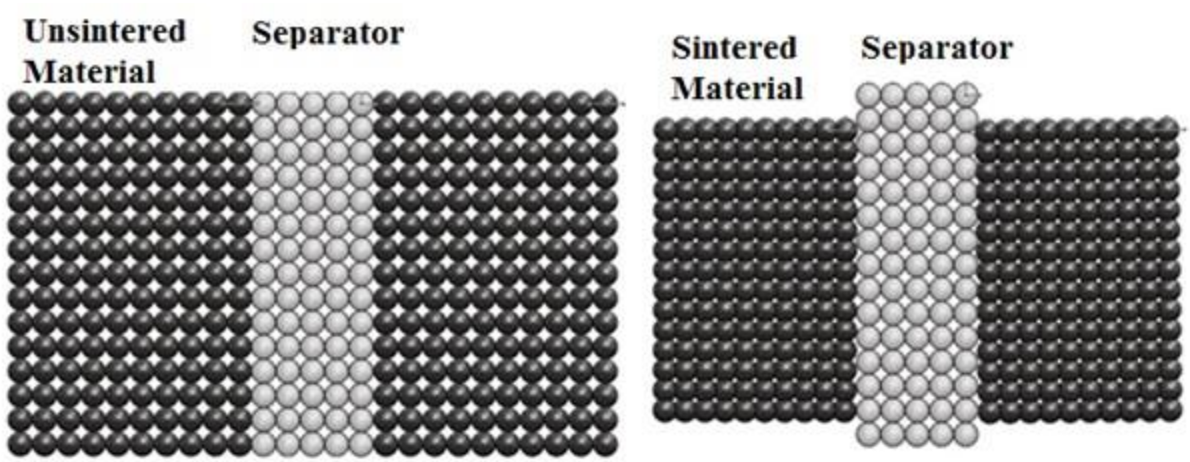


Figure 2. Sintering process for SSS. The blue line represents the heating ramp; the red line represents sintering temperature for the separator and the green line represents the sintering temperature for the base material.

An illusion is provided in Figure 3. The black spheres represent the B-powders and the white spheres represent the S-powders. Figure 3-a illustrates the S-powder after deposition into the B-powder layer. In the course of sintering, the B-powder spheres only fuse with the neighboring B-powder spheres to form a solid piece while the S-powder regions are still loose. The part is then separated with ease by removing the loose S-powder.



(a) (b)

Figure 3. Illustration for SSS principle (a) before sintering; (b) after sintering – B-material shrinks while S-material does not. (The black spheres represent the building material and the white spheres represent the separator)

3. Comparative Advantages of SSS

Selective melting and selective sintering, which use electron beam or laser beam, have very high machine cost and their operating and maintenance costs are also high [9]. The printing speed in these machines is also low because of the relatively slow scanning and surface sweeping speed by thin beams of electron or laser. As the part gets larger, the layer printing time, which is proportional to area of the part, increases considerably. Furthermore, ceramics 3D printing technologies are not commercially mature. Research on direct laser melting of ceramic powder has shown that crack formation and low surface quality are major obstacles to commercial success of these processes in making ceramic parts.

In contrast to the above processes, the printing time in SSS, which is linearly proportional to the size of the part, gets relatively shorter for larger parts. The S-powder in SSS is removed completely hence no contamination remains on the part or on sintering furnace. The cost of the SSS hardware is a fraction of all other machines for technologies. The part size in SSS can be adjusted by resizing the linear rails. Multiple materials can be used to fabricate parts using a single separator powder with high enough sintering temperature.

4. Preliminary Experiments

In the preliminary experiments, a prototype machine is built and several B-powders and S-powders pairs are tested to produce parts out of ceramics and metals.

4.1. SSS Prototype Machine

A SSS printer contains the B-powder spreading system and the S-powder deposition system. As illustrated in Figure 4, the B-powder spreading system further includes two tanks that move up and down and a roller or blade for smoothly spreading thin powder layers. During B-powder spreading, the storage tank rises a set distance to provide sufficient powder. The platform tank lowers one exact layer thickness which ensures the new powder layer to be one layer thickness. The S-powder deposition system includes the motion actuators and a piezo vibrator. The motion actuators include an XY stage that moves the nozzle along the planned path; a Z stage that moves the nozzle up and down; a rotation actuator that keeps the nozzle opening opposite to the direction of movement.

The S-powder deposition is controlled together by the piezo disc vibration and movement of the nozzle. In a confined conduit, the dry powder particles spontaneously form an arch that arrests the powder above it as shown in Figure 5-b. The arching effect is generally to be avoided in the industry for powder storage and transportation [10] but serves to turn off the powder flow in the SSS process. The arch pattern is stable unless proper vibration is applied. Vibration by a piezo disc (Figure 5-a) breaks the arch therefore powder flows through the nozzle as illustrated in Figure 5-c. When printing, the rotation of the nozzle coordinates with vibration to enable the S-powder deposition.

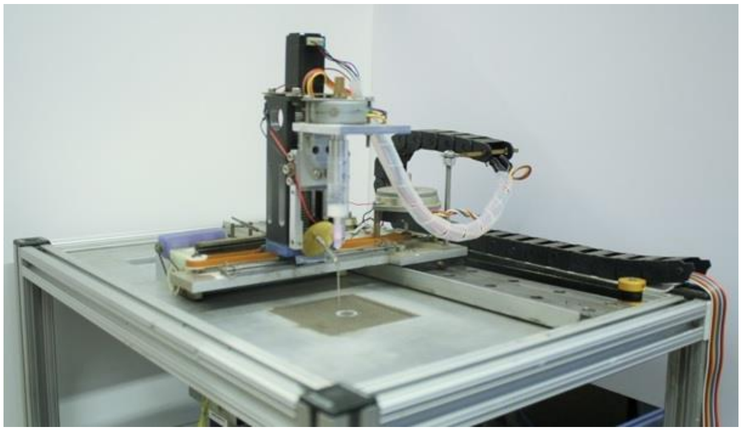


Figure 4. A Prototype SSS Machine

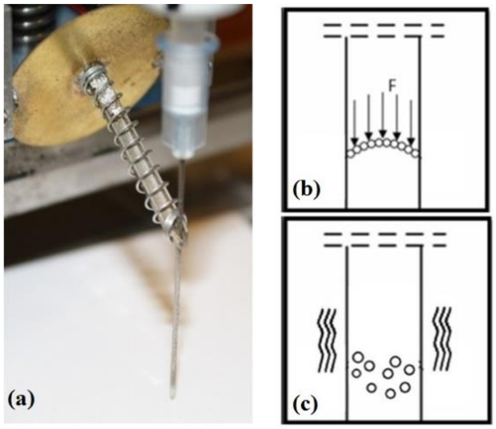


Figure 5. The dry powder delivery system (Left) The inhibitor deposition system (Right) Effect of vibration in breaking the powder arc

In the course of printing, the S-powder in the nozzle is always restricted by the B-powder below hence the deposition is not the same as powder flow through a nozzle whose outlet is not restricted by solid particles. Extensive research has been carried out to study powder flow through a conduit. The flow rate of powder in a nozzle is determined by the interaction between the nozzle and powder particles under an applied waveform. The phenomenon has been studied in numerous fields including drug delivery in pharmaceutical industry, food industry, cement industry, and powder spreading with multiple materials in 3D printing processes.

In case of restricted powder flow in SSS, there is an opening on one size of the nozzle near its end as in Figure 1-2. The powder can only flow out of the nozzle if there is an open space which can be made possible by the forward movement of the nozzle. The deposition rate of S-powder in SSS therefore adds the complexity of the nozzle movement and the interaction between the movements of S and B powders.

4.2. Pairing of S-powder with B-powder

Success of the SSS process depends on ease of separation of the part and non-part regions after sintering. Easy separation requires the S-powder to not bond, chemically nor mechanically, with itself and with the B-powder. At the sintering stage, the furnace temperature is below sintering temperature of the S-powder to avoid sintering but above sintering temperature of the B-powder for guaranteed sintering. A larger difference in sintering temperature between the S-powder and the B-powder will provide a safer window for setting the furnace temperature. Therefore, if the deposition criteria are satisfied, a S-powder with a very high sintering temperature can be used to pair with a large variety of B-powder candidates.

The investigated S-powders include ceramics and metals of high sintering temperature. S-powder candidates, spherical alumina and tungsten powders have proven to successfully produce parts in the SSS process. The B-powders used at this stage include lunar regolith simulant (JSC-1A) and bronze powder. JSC-1A is lunar regolith simulant provided by Orbitec.Inc. The purpose of testing lunar regolith simulant is to build landing pads, roads and structures on the moon by in-situ resource utilization, which is the lunar regolith [11]. The melting temperature of JSC-1A is described as 1100 °C [2] where experiments show that sintering can be carried out from 1100 °C to 1150 °C. The JSC-1A powder is sifted to be below 250 um. The bronze powder is sintered at 780 °C. A stainless steel powder of 316L is sintered at 1250 °C. The JSC-1A powder is paired with alumina powder. Bronze powder is paired with alumina and tungsten powder. Stainless steel is paired with tungsten powder.

4.3. Experimental Setup

The experiment can be divided into the printing stage and the sintering stage. In the printing stage, the S-powder is deposited into the B-powder layer after layer. To assist the later separation, assistive separation lines are printed, which divides the area surrounding the part into smaller sections. The assistive lines are especially important for separation of ceramic parts, where the sintered ceramics is too hard to cut and too brittle to endure impact. As illustrated in Figure 6, the white lines are deposited alumina as S-powder, the curves define the boundary of the part and the three straight lines are assistive separation lines which in this case divide the whole area into four sections, one of them being the part.

[2] www.orbitec.com

For JSC-1A, the printing layer thickness is 300 µm. The S-powder used is spherical alumina. The heating ramp for JSC-1A powder is set at 10°C/minute until the temperature reaches sintering stage. In the course of sintering, the JSC-1A powder is kept for 30 minutes to 60 minutes at a temperature from 900 °C to 1130 °C. For bronze, the printing layer thickness is 200 µm, the heating ramp is 5°C/minute and the powder is sintered at 780 °C for 30 minutes. The S powders used are spherical alumina or tungsten powder. For 316L stainless steel powder, the layer thickness is 200 µm and is sintered at 1250°C for two hours. The S-powders used are spherical tungsten powder.

Figure 6. Part boundary and assistive separation lines

4.4. Experimental results

Experiments show that all the sintered parts can be separated very easily. In the experiments for ceramics, with assistive lines dividing the powder bed into several individual sections, the sintered part is readily separable as each section shrinks towards its center as seen in Figure 7-a. The grey base material takes a reddish color as a result of oxidation in the ambient environment during the sintering process. The final part achieves the shape as it is designed (Figure 7-b). The white powder in the boundary falls off with ease. For the tile of this shape, many identical pieces form the interlocking pad for certain purpose (Figure 7-c). In this project, manufacturing of this tile is meant to produce functional tile, which will be used for building landing pads on Moon or Mars for spacecraft landing. In our experiments multiple ceramic parts have been fabricated with JSC-1A as illustrated in Figure 7-d.

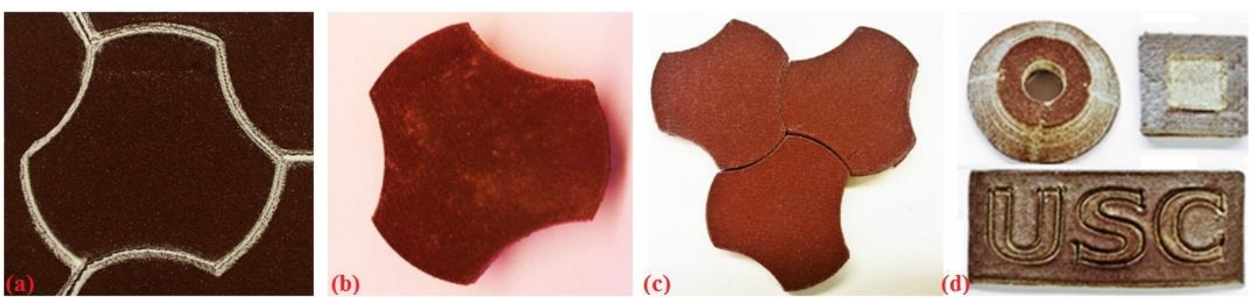


Figure 7. The sintered ceramic pieces of JSC-1A. (a) The sintered brick unit after sintering; (b) The separated brick unit; (c) Interlocking bricks pattern; (d)Variety of ceramic samples

Metallic parts have also been fabricated successfully for proof of concept purpose. A bronze piece of half cone shape is sintered with spherical alumina powder as the S-powder as illustrated in Figure 8-a. A bronze gear is fabricated with spherical tungsten powder as S-powder in Figure 8-b. A USC logo and the top view of a turbine are shown in Figure 8-c. The surfaces of the parts have been slightly polished.

(a) (b) (c)

Figure 8. SSS printed bronze parts a: Half cone b: Gear c: USC tag and turbine top

Initial experiments have also been carried out to test the capability of printing stainless steel parts. The results of a few early trials are demonstrated in **Error! Reference source not found.**

Figure 9. SSS printed 316L stainless steel parts

Sintering temperature of loose S-powders alone promises their capability to pair with a large variety of B-powder candidates. A maximum of 1500 °C is used to test S-powder for 1 hour in the ambient environment. Experiments show that at this temperature, alumina powder remains loose without sintering. From the literature, the sintering temperature for tungsten is about 2500 °C in a vacuum condition.

Table 1 Sintering temperature of ceramic and metallic powders

Materials	**Alumina**	**Tungsten**
Sintering Temperature / °C	>1500*	>2500

*By experiments

5. Discussion and research focus

It has been demonstrated that SSS is very capable for additive manufacturing of ceramic and metallic parts. The S-powders used in the experiments all remained loose after sintering. The difference of sintering temperature between the B-powders and the S-powders in the experiment is more than 400 °C for ceramics and more than 1000 °C for metals. Tungsten powder, which has a sintering temperature of 2500 °C, it can be used to separate almost all other metals and alloys as shown in Figure 10.

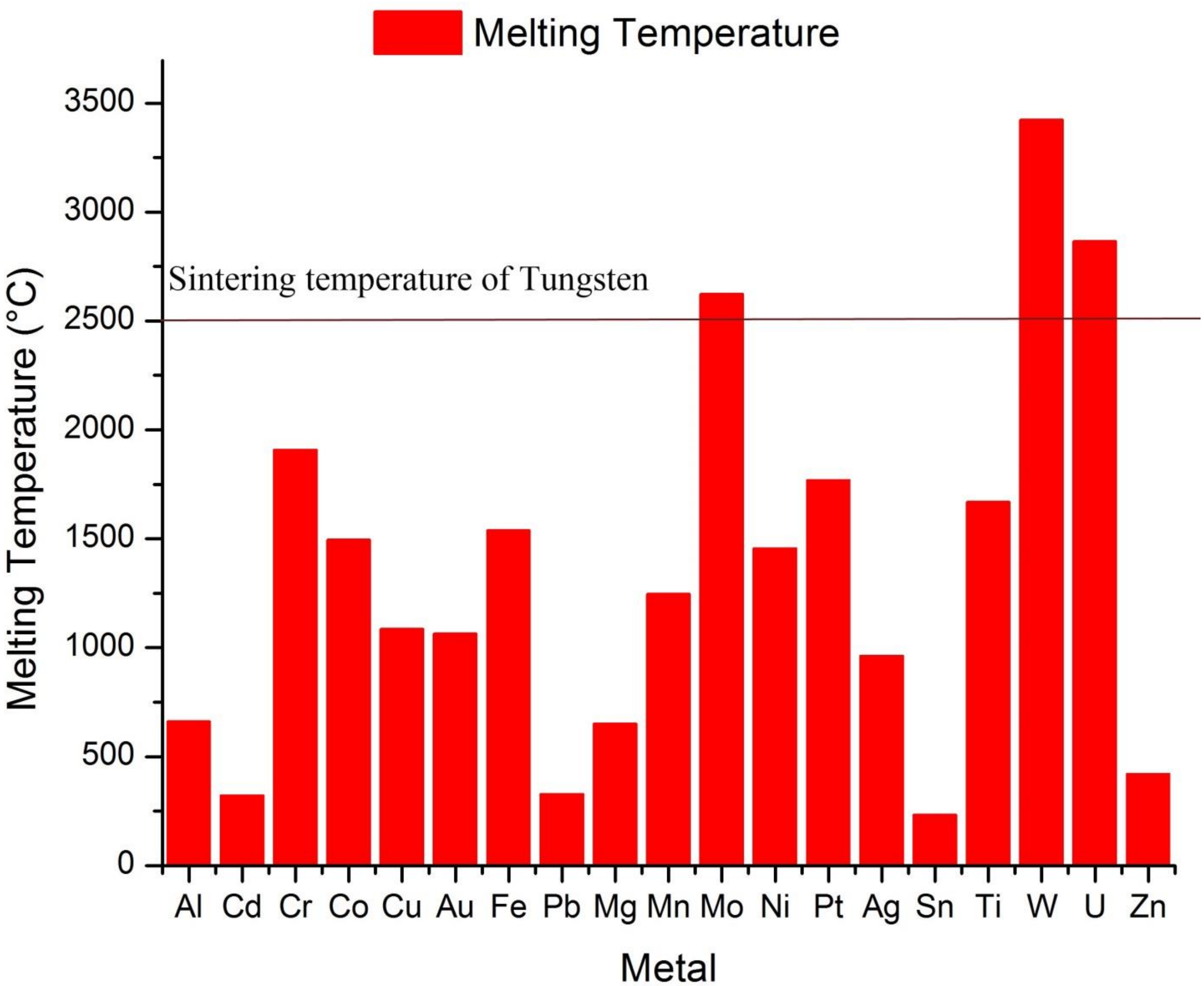


Figure 10. Sintering temperature of Tungsten relative to the melting temperature of other metals

Final parts are easily separated from the non-part materials after sintering. Assistive separation lines further increase the ease of separation from surrounding. Generally, the more assistive separation lines are added, the easier the part can be separated. However, the printing time is proportional to the total length of the separation lines. Research work to optimized separation lines is ongoing.

The resolution of SSS is determined by the separation line width. The consistency of S-powder deposition rate is the prerequisite for a smooth part. The inner diameter (ID) of the nozzle determines the finest achievable feature of the part. An overflow of S-powder causes contamination of the part and a waste of material while underflow causes difficulty in separation, even failure of separation. Study of a controlled dry powder deposition is also ongoing.

6. Conclusion

This research reported in this article has demonstrated that SSS is a promising technology as a metal/ceramic AM platform with capability to deliver high quality, multi-scale, high speed and at a comparatively low cost which makes the process affordable by consumer market. Besides the economic advantages, SSS has the promise to manufacture large scale industrial ceramic and metallic parts.

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