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# A review of bulk metallic glasses by selective laser melting

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## Abstract:

Bulk metallic glasses (BMGs) are a subject of interest due to their superior specific properties. However, BMGs are difficult to apply in industry due to their difficulty in manufacturing and secondary operation. Selective laser melting (SLM) can obtain relatively high cooling rates during the 'layer-by-layer' process. The main problems in SLM additive fabrication of amorphous alloys are cracks and crystallization. In this paper, based on the research of SLM additive manufacturing BMGs in recent years, the factors affecting crystallization and forming are discussed from many aspects according to different material systems. In addition, the mechanical, physical and chemical properties of BMGs are reviewed. Finally, the prospect of SLM in additive manufacturing of BMGs is provided.

*Keywords: Bulk metallic glasses; Selective laser melting; Additive manufacturing; Defects.*

## Introduction

Selective laser melting (SLM) can provide a suitable processing route for bulk metallic glasses (BMGs) [1,2]. The very high cooling rates occurring during the process are usually higher than the critical cooling rate of most BMGs [3]. The CCT diagrams of iron-based amorphous alloys prepared by different methods are shown in Figure 1. It is known from the figure that the cooling rate obtained by the SLM method is far greater than the critical cooling rate for the formation of iron-based amorphous alloys. However, high thermal gradients involved in the process combined with the intrinsic brittleness of most BMGs could cause severe defects like cracks or even delamination in the components produced by SLM [4]. Therefore, lots of efforts were carried out to overcome these defects in the process. At present, the research on the preparation of amorphous alloys by SLM is still in the initial stage, and a complete theory and technical path has not been formed. The current research mainly focuses on preliminary work such as process exploration, material design, and microstructure characterization. More basic SLM process calculations, crystallization mechanisms and predictions, and fracture behavior of materials have not been clearly explained. Therefore, it is very necessary to make a summary of the current research status of SLM preparation of amorphous alloys in the published literature and discuss its future development trend.

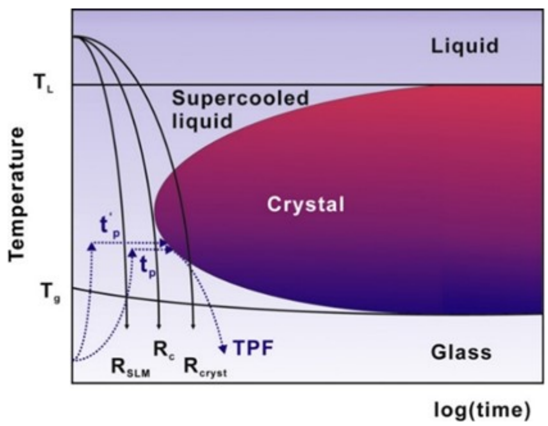


Fig. 1 CCT of Fe-based bulk metallic glass [3]

## 1. BMGs systems by SLM

In 2013, Pauly was the first to report that the Fe-based bulk metallic glass was formed by SLM technology, and the 3D scaffold structure was successfully manufactured [5]. Additive manufacturing of amorphous alloy powder by SLM requires the regulation of laser power, scanning speed, scanning distance and powder thickness. These parameters affect two important standards of amorphous 3D printing production: formation and crystallization. Although a higher cooling rate can inhibit crystallization, it is inevitable that high speed cooling rate will lead to the instability of the molten pool, resulting in bad molding in SLM. Thus, inhibition of crystallization and the perfect formation tend to be two conflicting requirements in the process of amorphous alloys manufacturing. The Archimedes drainage method is generally used to measure the density of 3D printed samples, but the surface of the printed samples is generally rough, and this roughness will capture small bubbles, thereby reducing the overall density. X-ray tomography (XRT) is a good choice to test the density of SLM samples. Ouyang [6] used XRT to measure the density of SLM parts, and the obtained density was higher than the Archimedes method. Most studies believe that density depends mainly on energy density. Li created a precedent in the research of aluminum-based BMGs by SLM additive manufacturing method and did some research on processing, microstructure evolution and mechanical properties of SLM Al-based amorphous alloys [4,7,8]. Deng [9] studied the biocompatible glass as Ti47Cu38Zr7.5Fe2.5Sn2Si1Ag2 alloy by SLM. The diffraction patterns of the SLM sample and the cast rod only show a large maximum scattering and look completely glassy. It is worth noting that although the cooling rate should be similar to gas atomization, the alloy will vitrify during the SLM process. Gao [10] studied the SLM Ti/Zr-based bulk metallic glass matrix composites (BMGCs) as (Ti0.65Zr0.35)90Cu10 alloy. There are amorphous phase, β phase and a small fraction of the (Ti, Zr) 2Cu phase in the alloy. Compared with those of the BMGCs fabricated using traditional technologies [11], Gao's work showed that the hardness and elastic modulus of the β and amorphous phases in the BMGC fabricated via SLM are both higher. It should be noted that the volume fraction of the amorphous phase in BMGCs is only approximately 20%.

## 2. Simulation of BMGs by SLM

At present, the simulation research on SLM-BMG mainly focuses on two aspects. One is crystallization, and the other is molding (such as cracks). Guo [12] used the HA bond type index method. The crystallization behavior occurs during the first heating and cooling process, which means that the atoms in the system have enough time to move above the temperature change rate and rearrange into an ordered structure at three different temperature change rates. However, the crystallization rate at different temperature rates is not consistent. To simplify the process, Lindwall [13][14] created a new model that took 0.12% less time to calculate, a nearly 1,000-fold increase in efficiency. The simulation results show that crystallization mainly occurs in the lower layers of the heating layer, that is, the solidified pool below the heat source. When it occurs during heating, although it does not melt, crystallization has occurred due to the surrounding temperature environment.

## 3. Mechanical properties of BMGs

Wang [15] conducted performance tests on Fe-based amorphous additive manufacturing and obtained an average nano-hardness of 14 GPa. The corresponding Vickers hardness is about 1260 HV. This hardness is even higher than that of direct metal laser sintering samples (902 HV), supersonic plasma spraying coatings (1005 HV) or similar alloy compositions of atmospheric plasma spraying samples (731±77 HV). In order to improve mechanical properties, many scholars tried to use other methods besides optimizing process parameters. Ouyang [16] found heat treatment of 3D printed Zr-based BMG at the temperature of supercooled liquid zone will toughen the molten pool and heat-affected zone. Li [17] increased the average hardness of the produced BMG and the uniformity of the hardness distribution by multiple scans. The addition of second phase particles can also significantly improve mechanical properties.

## 4. Conclusion

Many scholars have studied the manufacture of amorphous alloys through SLM, especially in recent years, which has become a research hotspot in the materials and engineering field. SLM-BMG's research focuses on two issues: forming and crystallization. Many studies have improved or solved these two problems through process parameters, scanning strategies, and optimization of alloy composition. The basic research of SLM-BMG for these things, its future development direction must be biased towards its functional applications, such as catalytic performance, biocompatibility and so on. It is not difficult to see that the research of SLM-BMG is just in its infancy and there is still a lot of work to be done.

## Conflict of Interest

The authors declare no conflict of interest.

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