Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

Recapitulation on Laser Melting of Ceramics and Glass-ceramics

M.X. Gan [a,b], C.H. Wong [a,*]

[a] Singapore Centre for 3D printing, School of Mechanical and Aerospace Engineering,
Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] SLM Solutions Singapore Pte Ltd, 25 International Business Park #02-15/17,
German Centre, Singapore 609916, Singapore.
*Email: chwong@ntu.edu.sg. Tel: +65 6790 5915.

Abstract

Additive manufacturing of ceramics and glass-ceramics is becoming important due to demands for high-performance applications and requirement for customizations. This is also due to the high cost incurred by conventional methods for producing prototypes and functional end parts of such inorganic materials. Despite the advantages that are already evident for direct laser melting of metals, in-process challenges such as thermal stress induced cracks and laser-material interactions have slowed down the progress and adoption of direct laser melting for these inorganic and non-metallic materials. Nevertheless, several works have been carried out to improve the process of direct laser melting of ceramics and glass ceramics despite the various challenges posed. In this article, we recapitulate past studies and update the progress on the additive manufacturing of ceramics and glass ceramics in particular by direct laser melting. In addition, we discuss the relevance of laser melting of ceramics and glass-ceramics for future roadmap.

Keywords

Keywords: Selective laser melting, additive manufacturing, LAS, glass-ceramic, spodumene.

Introduction

Additive manufacturing (AM), or three-dimensional (3D) printing, is a developing technology rapidly integrating into both the commercial and non-commercial world [1]. Due to the achievable design freedom, once known as rapid prototyping (RP), improved technologies attracted industries to manufacture functional end parts via AM processes. American Society for Testing and Materials (ASTM) F2792 defines AM as a manufacturing technique in which successively added materials in a layerwise fashion creates a full 3D part. Today, numerous systems are available in the market to cater to different applications [2]. These systems can be categorized into three large groups based on the material type: solid, liquid, and powder [2]. As such, the joining method differs depending on the materials (see Table. 1).

For instance, photopolymerization is used to join liquid-based polymers, while powder-based polymers can be joined either using binders via ink-jetting or sintering by a laser source. Joining of solid-based polymers, which mainly comes in the form of a filament, requires a heater embedded nozzle to heat the material to its softening point before deposition. In the case of metals, although one of the available methods uses the material in filament form [3], the rest used powders. Nevertheless, the joining method for all metal AM is similar to laser-welding. Two common types of lasers used in AM machines are the yttrium aluminum garnet fiber laser and CO_2 laser. These high-powered infra-red lasers either fully or partially melt the powder particles to create a 3D part. Due to the availability and advantages of these technologies, AM has also found itself a strong manufacturing candidate for aerospace, automotive, biomedical, and even in households' items.

Table 1: AM material and joining methodologies

Additive manufacturing			
Material format	Powder	Solid	Liquid
Material types	Metal/Non-metal	Metal/Non-metal	Non-metal
Joining means	Laser or Electron beam/Binder jetting	Laser/Heating coil	UV* source, material jetting
Joining methodology	Melting or sintering/Solidifying	Melting/Fusing	Photo-curing

*UV: Ultraviolet

AM does not only promote design freedom but also greatly reduces the time to fabricate a part. The labors at the assembly stage can be reduced or entirely removed as interconnecting parts can now be manufactured using AM processes. Prototypes, depending on the size and complexity, can be fabricated and assessed in a matter of hours to a few days. Furthermore, design modifications can be carried out virtually and quickly. These conveniences can potentially reduce the production costs and time to market.

Until today, the application of AM in most industries has been very focused on metals and polymers but barely on ceramics and glass-ceramics. Advanced ceramics have superior material properties for many engineering applications such as that in the automotive and aerospace industries [4]. However, the shaping of a ceramic part is very challenging through conventional methods due to the brittle nature and high tool wear rate. Furthermore, the complexity of manufacturing advanced ceramics is high as they also need to meet certain standards for satisfactory performances [5]. Similarly, the shaping of highly complex glass-ceramic parts is difficult due to increased viscosity caused by crystallization [6]. Fortunately, AM provides us a way to overcome these challenges faced in producing a geometrically complex ceramic part. As such, it is important to improve the fabrication process of AM for ceramics and glass-ceramics as they provide the possibility of both reducing cost and overcoming shaping challenges encountered in conventional processes.

Although there are several other articles which reviewed on the AM of ceramics, this article intends to focus and update the progress only on the laser melting of ceramics and glass-ceramics with recent studies [7-10]. The inclination to focus on laser melting process, such as selective laser melting (SLM), is due to the promising capability to fully melt the material without binders to produce a fully dense part [11].

Laser melting of ceramics

Laser engineered net shaping (LENS^{TM}) is an AM process in which material is deposited through a nozzle into the focus of a laser beam to form a 3D part [12]. Using this method, Niu, et al. [13] successfully fabricated thin wall structures from Al_2O_3/YAG and achieved a theoretical density of 98.6%. Furthermore, Niu, et al. [14] went on to fabricate crack-free Al_2O_3 specimens after studying the correlation between scanning speed and crack formation, and optimizing the process parameters. More recently, Li, et al. [15] conducted a rigorous study on the effect of all the deposition variables using pure Al_2O_3 which also lead to a successful fabrication of a bulk 3D part.

On the other hand, (SLM) of ceramics is generally more challenging as compared to LENS for several reasons. Firstly, the comparatively lower density of ceramic powders lowers the flowability preventing smooth material deposition. Even though there are techniques available such as spray drying to increase the particle size and thereby improving its flowability, to melt a larger particle will require a greater laser power. Furthermore, the layer thickness will increase and hence reduce the precision of the part. In addition, the use of a high-powered laser beam ionizes the air in the powder bed as it moves across the surface. As a result, the created plasma blows the particles away, complicating the fabrication process [16].

Secondly, SLM is a process which involves rapid melting and solidification. The large thermal gradient produces large thermal stress in the solidified part. As ceramics are inherently brittle, the experienced thermal shocks often result in cracks [17]. In a separate study, Wilkes, et al. [18] reported that pre-heating the material to more 1600 °C allows crack-free Al_2O_3/ZrO_2 specimens with the strength of more than 500 MPa to be manufactured.

The third challenge is the extremely low near infra-red (NIR) absorptance of ceramics. Although NIR lasers irradiate higher energy, ceramics do not readily absorb a majority of the radiation [19]. To overcome this issue, Juste, et al. [20] coated the Al_2O_3 particles with graphite-based colloidal suspension. As a result, large complex parts with more than 90% relative densities could be manufactured using an NIR laser.

Laser melting of glass-ceramics

Glass-ceramic is another interesting class of material, like ceramics, that we should be considering for AM. The attractiveness of a glass-ceramic, especially the lithium aluminosilicates, is their low coefficient of thermal expansion (CTE) [21]. This is a very useful property for improving thermal shock resistance in the case of laser melting AM. In addition, the composition of a glass-ceramic can be tailored, giving it a wide range of possible applications. Some of these potential applications are summarized in Figure 1.

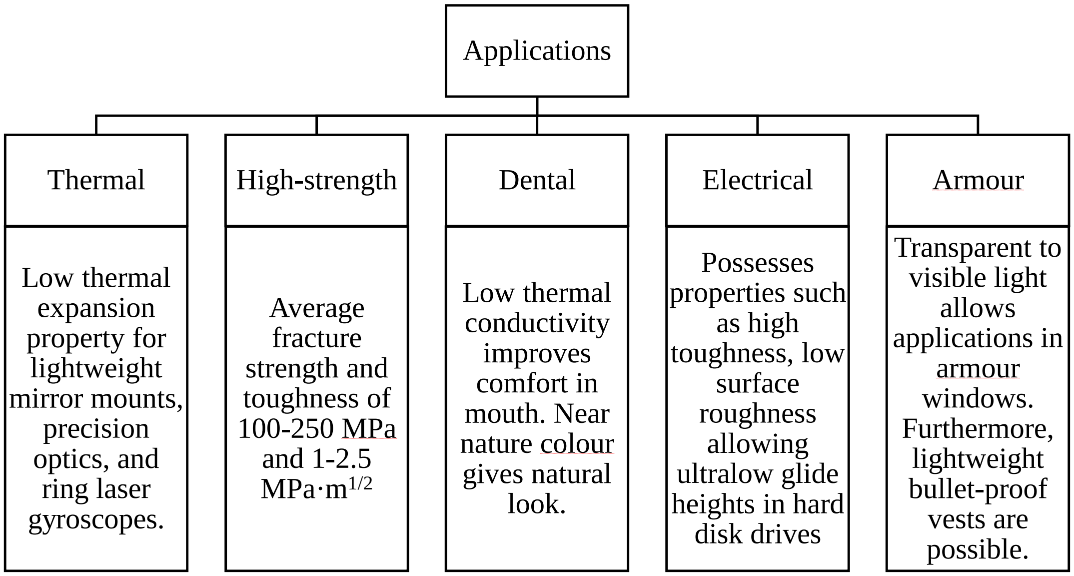

Figure 1: Some potential applications of glass-ceramics [22].

Despite the versatility of a glass-ceramic, there has been very little substantiated studies on shaping them using AM. For instance, two of the earliest studies on selective laser processing of lithium aluminosilicate (LAS) glass-ceramic by Gupta Manob and Cheng [23] and Zocca, et al. [24] was unable to produce 3D parts despite successful printing of dense tracks and single layers respectively. However, Gan and Wong [25] has recently reported their success in SLM of 3D but rather porous LAS glass-ceramic parts using spodumene mineral. In addition, a new study on a similar low expansion silica by Khmyrov, et al. [26] have also successfully laser melted crack-free tracks. Although limited, these studies are important for the process development of laser melting of ceramics and glass-ceramics.

Simulation studies

As in the case of laser melting of metals, experimental results alone are insufficient. To improve existing and develop new laser AM processes for ceramics, we need to understand the underlying thermophysical phenomenon. Simulation is an effective method which provides us with a deeper understanding in laser melting of these materials. For instance, simulations allow us to predict the outcome based on variables such as laser–material interaction, fluid flow of the melt pool, and thermal stress analysis. However, there is only a handful of studies simulating laser melting of ceramics available [27-30].

Moreover, a useful model alone is insufficient. Temperature-dependent material properties of new and useful ceramics and glass-ceramics need to be made available to benefit from the simulations.

Conclusion

The potentials seen in the laser melting additive manufacturing method should not be limited to metallic materials. The technology enabling AM of ceramic and glass-ceramic parts will definitely provide industries with alternatives such as enhanced properties for operating in higher temperatures and the highly corrosive environment.

Furthermore, several studies on laser melting of ceramic and glass-ceramic have shown encouraging results and possibility of this AM method suggest that we should not abandon this idea yet. In addition, laser melting of ceramics and glass-ceramics will remain relevant for years to come especially with ideas such as AM of extra-terrestrial materials [31]. When made possible, the cost of carrying payloads on rockets can be greatly reduced.

In conclusion, this article updated on the recent studies on laser melting of ceramics and glass-ceramics and highlighted the importance of these processes.

Acknowledgement

This project is funded under EDB-IPP, in collaboration between Singapore Centre for 3D Printing and SLM Solutions Singapore Pte Ltd.

References

[1] A. Bandyopadhyay, T. Gualtieri, S. Bose, Global Engineering and Additive Manufacturing, Additive Manufacturing 1 (2015).

[2] C.K. Chua, K.F. Leong, 3D PRINTING AND ADDITIVE MANUFACTURING: Principles and Applications (with Companion Media Pack) of Rapid Prototyping, World Scientific Publishing Co Inc2014.

[3] W.E. Frazier, Metal additive manufacturing: a review, Journal of Materials Engineering and Performance 23(6) (2014) 1917-1928.

[4] Y. Liang, S.P. Dutta, Application trend in advanced ceramic technologies, Technovation 21(1) (2001) 61-65.

[5] C.B. Carter, M.G. Norton, Ceramic materials: science and engineering, Springer Science & Business Media2007.

[6] S. Knickerbocker, M.R. Tuzzolo, S. Lawhorne, Sinterable β ‐ Spodumene Glass ‐ Ceramics, Journal of the American Ceramic Society 72(10) (1989) 1873-1879.

[7] W. Yeong, C. Yap, M. Mapar, C. Chua, State-of-the-art review on selective laser melting of ceramics, High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal, 1–5 October, 2013, p. 65.

[8] N. Travitzky, A. Bonet, B. Dermeik, T. Fey, I. Filbert ‐ Demut, L. Schlier, T. Schlordt, P. Greil, Additive Manufacturing of Ceramic ‐ Based Materials, Advanced Engineering Materials 16(6) (2014) 729-754.

[9] A. Zocca, P. Colombo, C.M. Gomes, J. Günster, Additive manufacturing of ceramics: issues, potentialities, and opportunities, Journal of the American Ceramic Society 98(7) (2015) 1983-2001.

[10] S.L. Sing, W.Y. Yeong, F.E. Wiria, B.Y. Tay, Z. Zhao, L. Zhao, Z. Tian, S. Yang, Direct selective laser sintering and melting of ceramics: a review, Rapid Prototyping Journal 23(3) (2017).

[11] S. Bremen, W. Meiners, A. Diatlov, Selective laser melting, Laser Technik Journal 9(2) (2012) 33-38.

[12] G.K. Lewis, E. Schlienger, Practical considerations and capabilities for laser assisted direct metal deposition, Materials & Design 21(4) (2000) 417-423.

[13] F. Niu, D. Wu, G. Ma, J. Wang, J. Zhuang, Z. Jin, Rapid Fabrication of Eutectic Ceramic Structures by Laser Engineered Net Shaping, Procedia CIRP 42 (2016) 91-95.

[14] F. Niu, D. Wu, S. Yan, G. Ma, B. Zhang, Process Optimization for Suppressing Cracks in Laser Engineered Net Shaping of Al2O3 Ceramics, JOM 69(3) (2017) 557-562.

[15] Y. Li, Y. Hu, W. Cong, L. Zhi, Z. Guo, Additive manufacturing of alumina using laser engineered net shaping: Effects of deposition variables, Ceramics International 43(10) (2017) 7768-7775.

[16] Q. Liu, B. Song, H. Liao, Microstructure study on selective laser melting yttria stabilized zirconia ceramic with near IR fiber laser, Rapid Prototyping Journal 20(5) (2014) 346-354.

[17] Y.-C. Hagedorn, J. Wilkes, W. Meiners, K. Wissenbach, R. Poprawe, Net shaped high performance oxide ceramic parts by selective laser melting, Physics Procedia 5 (2010) 587-594.

[18] J. Wilkes, Y.-C. Hagedorn, W. Meiners, K. Wissenbach, Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting, Rapid Prototyping Journal 19(1) (2013) 51-57.

[19] N.K. Tolochko, Y.V. Khlopkov, S.E. Mozzharov, M.B. Ignatiev, T. Laoui, V.I. Titov, Absorptance of powder materials suitable for laser sintering, Rapid Prototyping Journal 6(3) (2000) 155-161.

[20] E. Juste, F. Petit, V. Lardot, F. Cambier, Shaping of ceramic parts by selective laser melting of powder bed, Journal of Materials Research 29(17) (2014) 2086-2094.

[21] D. Krause, H. Bach, Low thermal expansion glass ceramics, Springer Science & Business Media2005.

[22] E.D. Zanotto, Bright future for glass-ceramics, American Ceramics Society Bulletin 89(8) (2010) 19-27.

[23] L.L. Gupta Manob, J.F.Y. Cheng, POROUS Li2O A12O3 SiO2 (LAS) GLASS-CERAMICS PREPARED BY SELECTIVE LASER MELTING AND ANNEALING, Ceramic Engineering and Science Proceedings, American Ceramic Society, 1980, p. 523.

[24] A. Zocca, P. Colombo, J. Günster, T. Mühler, J.G. Heinrich, Selective laser densification of lithium aluminosilicate glass ceramic tapes, Applied Surface Science 265 (2013) 610-614.

[25] M. Gan, C. Wong, Properties of selective laser melted spodumene glass-ceramic, Journal of the European Ceramic Society (2017).

[26] R. Khmyrov, C. Protasov, S. Grigoriev, A. Gusarov, Crack-free selective laser melting of silica glass: single beads and monolayers on the substrate of the same material, The International Journal of Advanced Manufacturing Technology 85(5-8) (2016) 1461-1469.

[27] J. Li, L. Li, F. Stott, Comparison of volumetric and surface heating sources in the modeling of laser melting of ceramic materials, International journal of heat and mass transfer 47(6) (2004) 1159-1174.

[28] J. Li, L. Li, F. Stott, A three-dimensional numerical model for a convection–diffusion phase change process during laser melting of ceramic materials, International Journal of Heat and Mass Transfer 47(25) (2004) 5523-5539.

[29] Q. Chen, G. Guillemot, C.-A. Gandin, M. Bellet, Finite element modeling of deposition of ceramic material during SLM additive manufacturing, MATEC Web of Conferences, EDP Sciences, 2016, p. 08001.

[30] C. Protasov, R. Khmyrov, S. Grigoriev, A. Gusarov, Selective laser melting of fused silica: Interdependent heat transfer and powder consolidation, International Journal of Heat and Mass Transfer 104 (2017) 665-674.

[31] A. Goulas, D.S. Engstrom, R.J. Friel, R.A. Harris, Investigating the additive manufacture of extra-terrestrial materials, (2016).