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Design for Metal Additive Manufacturing: An Investigation of Key Design Application on Electron Beam Melting

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***Abstract*—**Electron beam melting (EBM) is one of the modern additive manufacturing (AM) technologies. In EBM, the electron beam melts metal powder into a fully solid part layer by layer. Since EBM is a new technology, most designers are unaware of the capabilities and the limitations of EBM technology. Also, many engineers are facing many challenges to utilize the technology because of a lack of design rules for the technology. The aim of this study is to identify the capabilities and the limitations of EBM technology in fabrication of small features and overhang structures and develop a design rules that need to be considered by designers and engineers. In order to achieve this objective, a series of experiments are conducted. Several features having varying sizes were designed, fabricated, and evaluated to determine their manufacturability limits. In general, the results showed the capabilities and limitations of the EBM technology in fabrication of the small size features and the overhang structures. In the end, the results of these investigation experiments are used to develop design rules. Also, the results showed the importance of developing design rules for AM technologies in increasing the utilization of these technologies.

***Keywords*—**Additive manufacturing, design for additive manufacturing, electron beam melting, self-supporting overhang,

I. Introduction

EBM is a powder-bed-fusion AM process in which a fully solid part is directly fabricated layer by layer from CAD. The unique capabilities of EBM have opened the door for this technology in high performance application like medical implants, aerospace, and automotive. However, the unavailability of the Design for Additive Manufacturing (DFAM) rules for AM technologies also familiarity of the designers' mind with the design rules or rules for traditional manufacturing methods are the most challenges for the designers to take full use of the unique capabilities brought by AM. DFAM is a design method that considers the functional performance and other product consideration like manufacturability, reliability, and the cost of the AM objects. DFAM gives the designers and engineers the opportunities to utilize the unique capabilities of AM to improve the functional performance of the products.

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Some researchers gave attention to develop design rules for AM technologies. Seepersad et al. developed a design guideline for dimensioning and tolerancing parts that are producing selective laser sintering (SLS) technology. The capabilities and limitations of the technology are identified [1]. Ranjan et al. proposed systematic graph-based approach to implement design guidelines in AM. The relationship between AM process parameters and input part geometry is used to create the design rules. The developed rules helped the designers to design the models with efficient part designs that can be manufactured with minimum part errors [2]. Kranz et al. developed a design guideline for laser additive manufacturing (LAM). The effects of part position and orientation on the dimension accuracy and surface quality are experimentally investigated. Basic shapes which involved bars, thin walls, and bore holes with varying diameters were built in different orientations to determine the process limits [3].

Thomas developed design rules for selective laser melting (SLM). The small size features and the self-supporting overhanging surfaces are identified experimentally [4]. EBM is relatively new AM technology, where it is classified as metal AM and as powder beds AM technology. This technology allows for the producing of complex, multi-functional metal objects from CAD model directly [5]. A wide range of metals and metals alloys have been processed using metal AM technologies, like titanium, and aluminum alloys [6], nickel Alloys [7], [8] steel alloys etc. Recently, attention is given to EBM as a new technology. A lot of research has been done on evaluation of the mechanical properties and microstructures of the parts produced by EBM [9]. Processing of the metals alloys (powder based) using EBAM technology resulted in superior mechanical properties and microstructures compared with wrought products [10]. Little attention has been given to the developing design rules for EBM. Vayre et al. investigated the manufacturability constraints of the EBM process. The removing of the unbound powder and the need for supporting structures are considered in this study. The authors studded the effect of the duration and the cross-section area and type on the depth of the removed powder. In the case of support structure, the authors built thin samples with different orientation angles and observed the distortion which was very high when the built surface is parallel to the stare plate. The distance between the stare plate and the first layer effect is studied. It is shown that when the distance is from 0.05-0.1 mm, it is hardly to measure the deformation and it is shown that there is no difference in terms of deformation when the distance changes form 5-10-15 mm. Also, the impact of the support density is considered. The results showed that the effect of the support density has an impact on surface flatness [11]. Vora et al. demonstrated new capabilities of EBM and selective laser melting (SLM) processes to build overhanging surfaces without supports structures using the blended powder approach. Al-Si and Ti64-Cu alloy systems were successfully processed, and unsupported overhang surfaces having dimension 5 mm were produced without warping. The SLM produced parts showed that there are no signs of warping deformation. Compared to benchmarking results with Ti64 that are fabricated using of EBM, height of warp was reduced from 2.7 mm to 0.3 mm (88%) [12]. Rami and Frederic proposed a methodology for designing and optimizing support structures in EBM process. New support structures are used, and their efficiency is studied. The results showed an enhancement for reducing geometric defects [13]. EBM process is still unknown technology for many designers and engineers. DFAM approach has to be used to identify the limitations and challenges that have to be considered by designers and engineers. In this study, the capabilities and challenges of EBM that have to be considered by designers and engineers are identified.

II. Excremental Procedures

A. Benchmark Parts

Benchmark parts are designed and fabricated to evaluate the capabilities and the limitations of producing the small features and overhang structures via EBM process. Most of the considered features are fabricated with varying dimensions to obtain their effects. The selected benchmark parts are described in the following section.

B. Minimum Resolvable Feature Size

In this investigation, the manufacturability of the small fundamentals features like round holes, walls thicknesses, round bares, cubed slots, and round slots flat walls is evaluated. The features were designed in size series and prepared for fabrication. Fig. 1 shows the small features configurations.

C. Overhangs Structures

Most of the AM are unable to build the overhang structures without proper support. EBAM is working under a powder-bed-fusion AM process in which the build parts are immersed on loose powder in the powder bed, so that ideally using the support structures to support the overhang surfaces is not necessary. On the other side, the loose powder is not sufficient to support the liquid melting metal and not sufficient to take away the heat from the overhang surface because the loose powder is not thermally conductive, and this leads to dross formation, distortions, warping [14], [15]. Controlling the limits of adding the support structure to the overhang surfaces is one of the design rules that should be obtained. In this investigation, three fundamental overhangs are considered in order to identify the self-supporting limits. The selected overhang structures include angle overhang with varying angles, convex overhang with varying radius, and hole overhang with varying diameters as shown in Fig. 2.

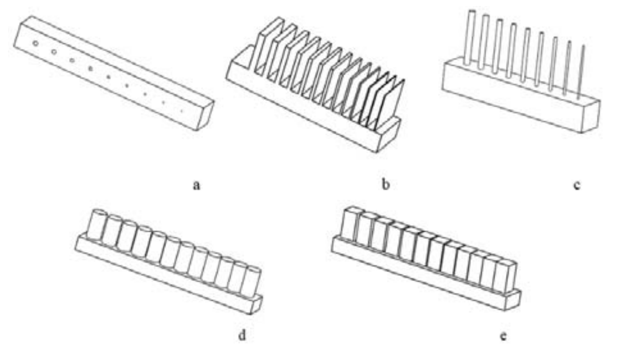

Fig. 1 Features configurations (a) round holes (b) walls thickness (c) round bars (d) round slots (e) cubed slots

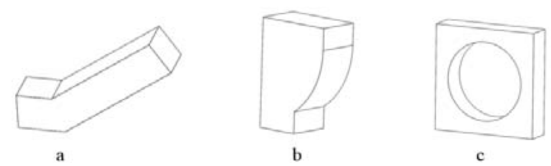

Fig. 2 Overhang structures (a) angle overhang (b) convex overhang (c) round hole overhang

D. Material and Equipment

The material that is used to fabricate the tests specimens in this study is Ti6Al4V in powder form with particles size of 30-50 μm. The chemical compositions of Ti6Al4V powder were Al (6.04%), V (4.05%), C (0.013%), Fe (0.0107%), and O (0.13%), with the rest as Ti in weight percent. ARCAM A2 machine was used for fabricating the test specimens with default preheat and melting parameters. The fabricated specimens are then subjected to the powder recovery system (PRS) to blast the sintered powder using compressed air. The fabricated specimens are evaluated first thorough visual inspection then optical microscope or profile projector.

III. Results and Discussion

A. Minimum Resolvable Feature Size

This section presents the result of fabrication the small features via EBM. Fig. 3 shows some of fabricated small features.

B. Small Holes

In order to evaluate the manufacturability and the quality of the fabricated round holes in small diameters, holes of 0.1 mm to 0.9 mm diameter with increment of 0.1 mm were designed and fabricated as shown in Fig. 4. The manufacturability of the small holes was evaluated using optical microscope as shown in Fig. 5.

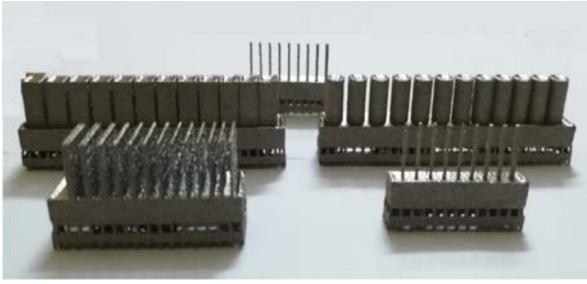

Fig. 3 Fabricated test specimens by EBM

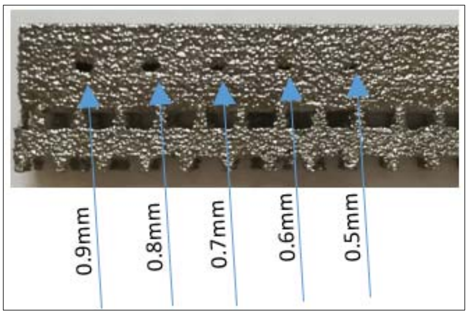

Fig. 4 Small fabricated holes

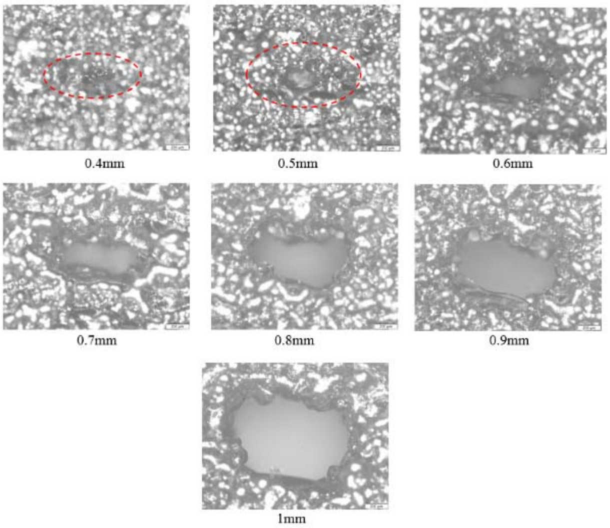

Fig. 5 Small holes by microscope

From Fig. 5, it is clear that the smallest hole that can be produced by EBM is 0.5 mm. For a 0.4-mm diameter hole, only a mark is produced on the surface of the fabricated part. Also, it is clear that all holes with diameter less than 0.9 mm were produced with an irregular shape. Further investigation has been done with increase of the diameter of the holes by 1 mm. Profile projector was used to evaluate holes having diameters greater than 1 mm as shown in Figs. 6 and 7. It is used to evaluate the manufacturability and the quality of fabricated holes.

The shadowgraph images showed that the smallest hole diameter that has round shape is 3 mm, and the shape improves with increasing of the hole diameter.

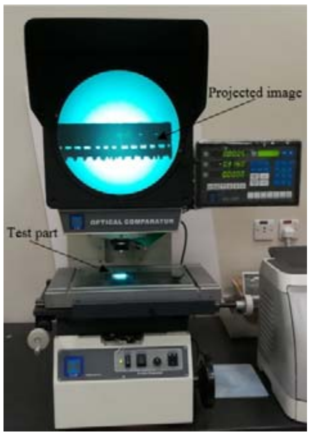

Fig. 6 Profile projector

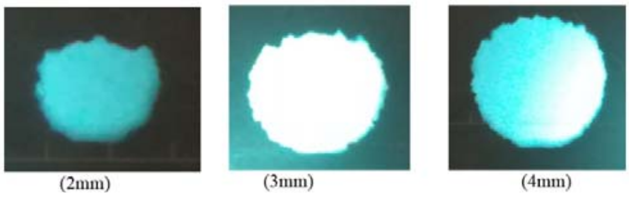

Fig. 7 Shadowgraph images of small round hole

C. Minimum Wall Thickness

To identify the minimum wall thickness that can be manufactured using EBM, a test part consists of plates having thicknesses form 0.1 mm to 1 mm with increments of 0.1 mm and from 1 mm to 1.6 mm with increments of 0.2 mm. The plates were built vertically at 90º then were cleaned and prepared for evaluation. The fabricated parts were evaluated using the shadowgraph as shown in Fig. 8.

The results indicated that the minimum thickness that can be produced by EBM is 0.6 mm, and it is shown that the designed thickness having dimensions less than 0.6 mm was produced with 0.6 mm thickness. All fabricated plates were straight and full density and free from any defects.

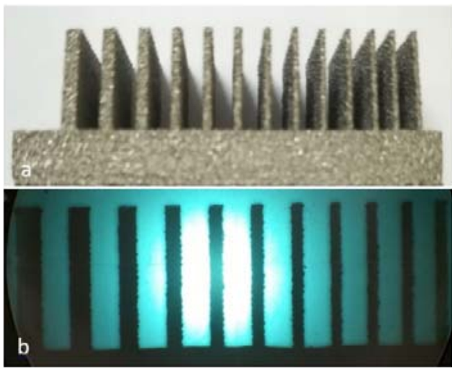

Fig. 8 Small wall thickness (a) Test part (b) Shadowgraph image

D. Minimum Round Bar

To evaluate the manufacturability and quality of the smalls round bars by EBM, a test part consists of bars having different diameters from 0.2 mm to 1 mm with increments of 0.1 mm. The bars were built vertically at 90º then cleaned and prepared for evaluation. The fabricated bares were evaluated using the shadowgraph as shown in Fig. 9. The results showed that the minimum round bar that can be produced by EBM is 0.65 mm in diameter and the designed bars having diameters less than 0. 6 mm were produced with 0.65 mm diameters. The results also showed that the round bars having diameters less than 0.9 mm were produced with some bend, and the bend increases with decrease in the bares diameters. It is also worth noting that the surface quality of the parts has effect on the capability of EBM to manufacture the accurate small round bars.

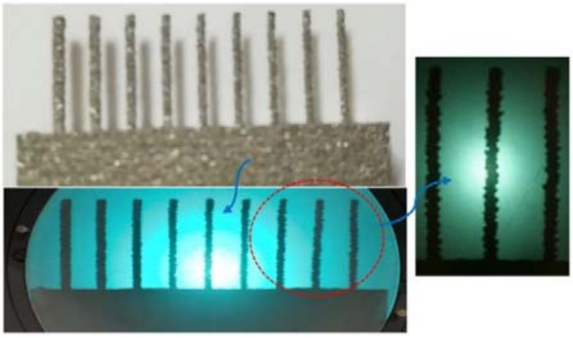

Fig. 9 Test part and shadowgraph images of small round bars

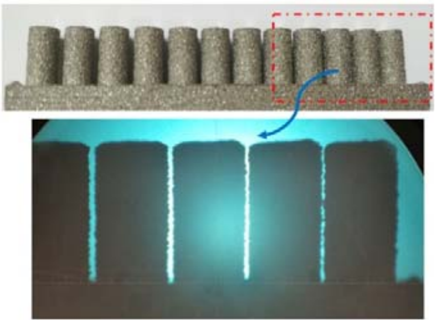

Fig. 10 Test part and shadowgraph image of small round slots size

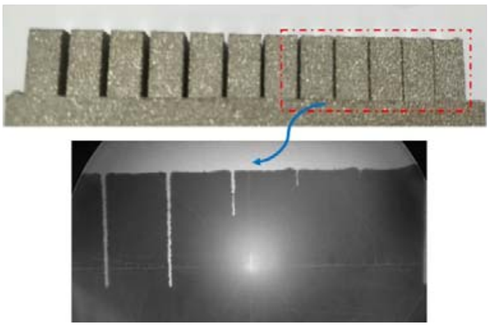

Fig. 11 Test part and shadowgraph images of the cubed slots

E. Minimum Round and Cubed Slots Size

In order to identify the minimum round and cubed slots size, two test parts round and cubed slots were designed and evaluated using the shadowgraph as shown in Figs. 10 and 11. The first part consisted of 5 mm diameter cylinders with height 10 mm, and the slots between the cylinders have dimensions varying from 0.1 mm to 1 mm with increments of 1 mm and second part consisted of 5 mmx5 mmx10 mm cubed bars, and the slots between the cubes have the same dimensions of the round slots. The parts were built vertically at 90º as shown in Figs. 10 and 11. The minimum slot size was found to be 0.2 mm in the case of round slots and 0.4 mm in the case of cubic slots (fully open). As shown in Fig. 10, the slot with dimension 0.1 mm has a full thorough along the height and depth, but the cylinders are connected by the extreme points of the cylinders. In the case of cubed slots, the slot with dimension 0.1 mm produced with 0.84 mm thorough slot along the height and 1.38 mm thorough height for 0.2 mm slot and 3.55 thorough height for 0.3 mm, were full thorough height for 0.4 mm slot. The reason that made the difference between round and cubed slots is that, in the cubed slots, much power is concentrated between the cubes which results in adhesion the sounding powder and case the block in the slots. It is also worth noting that the surface quality of the parts affects the capability of EBM to manufacture the small slots.

F. Overhangs Structures

This section presents the result of fabrication the overhang structure via EBM. Fig. 11 shows some of fabricated overhang specimens.

Fig. 12 Fabricated overhang test specimens by EBM

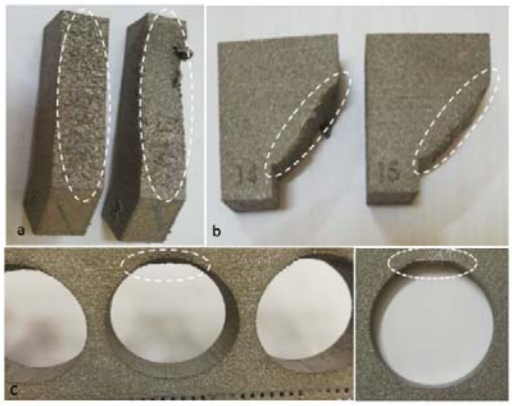

Fig. 13 Overhang structures distortions

In general, the results showed that it is possible to fabricate the considered overhang structures without support structures up to certain values then the distortions appeared, where the addition of the support structures is essential.

It is found that the lowest overhang angle that can be fabricated via EBM without support structure is 50 degrees and building of angle overhang with angle less than 50º resulted in distortion in the down face of the overhand (negative material) as shown in Fig. 13. In case of convex overhang, the result showed that the 7-mm radius is the maximum self-supporting convex overhang and the convex overhang with radius greater than 7 mm is produced with distortion in the down face of the overhand (negative material) as shown in Fig. 13. Finally, the result showed the maximum self-supporting round hole diameter is 18 mm where producing the round hole overhang with diameters greater than 17 mm resulted in dross formation that loses the circular form of the fabricated holes as shown in Fig. 13.

IV. Conclusions

This article presents a snapshot of the designed experiments that determine the EBM capability of manufacturing of the small features.

In general, the results showed that the minimum though round hole is 0.5 mm diameter, the minimum wall thickness, minimum round bar, minimum round slot and minimum cubed slot that can produced by EBM are 0.6 mm, 0.65 mm, 0.1 mm and 0.4 mm, respectively. Also, the results showed the lowest self-supporting angle overhang is 50 degrees, the smallest radius of self-supporting convex curve overhang is 7 mm radius, and the smallest self-supporting hole is 18 mm diameter.

The change of the material builds orientation, and the process parameters will result in change of the manufacturability limitations. For future work, other features could be considered and the effect of features orientation as well as the process parameters could be investigated.

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References

[1] Seepersad, C. C., Govett, T., Kim, K., Lundin, M. and Pinero, D. (2012) ‘A designer’s guide for dimensioning and tolerancing SLS parts’, Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX, pp.921–931.

[2] Rajit Ranjan, Rutuja Samant and Sam Anand (2015), ‘Design For Manufacturability In Additive Manufacturing Using A Graph Based Approach’, the ASME 2015 International Manufacturing Science and Engineering Conference MSEC2015, June 8-12, North Carolina, USA.

[3] J. Kranz, D. Herzog, and C. Emmelmann (2015), ‘Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4’, Journal Of Laser Applications.

[4] Thomas D. The development of design rules for selective laser melting: University of Wales; 2009.

[5] Murr LE, Gaytan SM, Ramirez DA, Martinez E, Hernandez J, Amato KN, et al. Metal fabrication by additive manufacturing using laser and electron beam melting technologies. Journal of Materials Science & Technology 2012;28:1-14.

[6] Calignano F. Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. Materials & Design 2014;64:203-13.

[7] Ö. Poyraz* EY, G. Akbulut*, A. Orhangül*, S. Pilatin*. Investigation Of Support Structures For Direct Metal Laser Sintering (Dmls) Of In625 Parts. International Solid Freeform Fabrication Symposium. Austin, Texas, USA2015.

[8] Abe F, Osakada K, Shiomi M, Uematsu K, Matsumoto M. The manufacturing of hard tools from metallic powders by selective laser melting. Journal of materials processing technology 2001;111:210-3.

[9] Cormier D, Harrysson O, West H. Characterization of H13 steel produced via electron beam melting. Rapid Prototyping Journal 2004;10:35-41.

[10] Murr L, Esquivel E, Quinones S, Gaytan S, Lopez M, Martinez E, et al. Microstructures and mechanical properties of electron beam-rapid manufactured Ti–6Al–4V biomedical prototypes compared to wrought Ti–6Al–4V. Materials characterization 2009;60:96-105.

[11] Vayre B, Vignat F, Villeneuve F. Identification on some design key parameters for additive manufacturing: application on electron beam melting. Procedia CIRP 2013;7:264-9.

[12] Vora P, Derguti F, Mumtaz K, Todd I, Hopkinson N. Investigating a Semi-Solid Processing Technique Using Metal Powder Bed Additive Manufacturing Processes. 24th Annual International Solid Freeform Fabrication Symposium-An Additive Manufacturing Conference, Austin, TX, USA2013.

[13] RamiTOUNSI FV. New concept of support structures in Electron Beam Melting manufacturing to reduce geomtricdefects. 15e Colloque National AIP-Priméca2017.

[14] Ameen, Wadea, Abdulrahman Al-Ahmari, Muneer Khan Mohammed, and Syed Hammad Mian. (2018). "Manufacturability of Overhanging Holes Using Electron Beam Melting." Metals (2075-4701) 8, no. 6.

[15] Ö. Poyraz*, E. Y., G. Akbulut*, A. Orhangül*, S. Pilatin*. Investigation Of Support Structures For Direct Metal Laser Sintering (DMLS) OF IN625 PARTS. in International Solid Freeform Fabrication Symposium. 2015. Austin, Texas, USA.