

APPLICATION OF ELECTRON BEAM MELTING (EBM) IN ADDITIVE MANUFACTURING OF AN IMPELLER

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ABSTRACT: An industrial impeller has been successfully fabricated by using Ti-6Al-4V ELI powder via a newly installed Arcam A2XX electron beam melting (EBM) machine. EBM was found to be preferable to build the circular or complex-shaped parts with thin walls. Several problems that frequently take place during the EBM fabrication are proposed based on the practical experience. It is found that metallization peeling-off, warpage, “swelling” and arc trips are the main reasons resulting in the failures of building jobs. It is suggested to pay close attention to the following aspects: a thorough cleanliness of the entire EBM system before start, a reasonable placement of builds on the start plate, an optimized design on geometries, etc., for a successfully built part.

INTRODUCTION

Integrating metallic additive manufacturing technologies into the manufacturing industry is of great interest currently as can be seen by the investments made by various countries such as China, U.S. and Singapore (Sun & Wei 2013; Anderson 2013). One such additive manufacturing technology is electron beam melting (EBM). EBM is an additive manufacturing technique using an electron beam to selectively melt a metallic powder bed directed by a computer added design (CAD) model. EBM is capable of producing functional parts with high mechanical properties more rapidly and more energy-efficiently as compared to laser based metallic additive manufacturing technologies, such as selective laser melting (SLM) (Chua et al. 2010).

Additive manufacturing of complex industrial parts, e.g. fuel nozzles, turbine blades, turbocharger wheels, pump impellers, etc., has been carried out around the world recently (Quail et al. 2009; Lu et al. 2013; MacMasters et al. 2013). Due to the inherent advantages compared to conventional forming technologies, such as investment casting, additive manufacturing is being explored for the manufacturing of such complex parts. As additive manufacturing technology matures, the challenge to directly produce large scale complex parts that surpasses the manufacturing capabilities of conventional forming processes can be seen by objectives mentioned by the U.S. Naval Research Laboratory in wanting to create thin wall (~2 mm) and large scale (~2 m) parts with complex internal geometry (Cooper 2014). Nanyang Technological University, Singapore has also invested in large scale additive manufacturing technology in the form of Arcam A2XX EBM which has a built volume of $\Phi 350 \times 380 \text{ mm}^3$ (Arcam AB2014). In addition to the advantages such as the rapid manufacturing process and high energy efficiency, electron beam melted parts are also reported to have less residual stresses as compared to laser based processes (Chua et al. 2010). Thus, post-processing heat treatment may not be necessary for the EBM built functional parts. Moreover, EBM has no issues with reflection in the molten pool, as a result that some certain materials unsuitable for laser based processes could be manufactured by EBM (Chua et al. 2010). These advantages thus provide motivation in industrial feasibility studies and fundamental research in order to fully understand the capabilities of this technology and future improvements to technology.

Ti-6Al-4V is the most widely used Ti alloy. Due to its high specific strength-to-weight ratio and outstanding corrosion resistance, Ti-6Al-4V has shown a great application perspective in aerospace, marine & offshore, etc. (Royer & Collings 1993). In this work, an attempt was made to explore the possibility of producing industrial parts via a newly installed EBM machine, prealloyed Ti-6Al-4V powder is used for building a centrifugal impeller. This work thus aims at addressing some technological problems encountered in EBM building process and showcasing the potential of such a technology in the additive manufacturing of complex industrial parts.

EXPERIMENTAL

A SLDPRT file of an industrial impeller was obtained from an open source website (GrabCAD 2014). The impeller produced for evaluation was built using an Arcam A2XX (Arcam AB, Sweden) EBM machine (Figure 1a), which is newly installed at NTU Additive manufacturing Centre (NAMC). The Arcam A2XX is the largest EBM machine available currently (Arcam AB, 2014). It offers a build envelope of $\Phi 350 \times 380 \text{ mm}^3$. It consists of two main cabinets, i.e. the electrical control cabinet and the vacuum chamber cabinet. Figure 1b illustrates a simple schematic view of EBM system. The electron beam is generated within an electron gun via a tungsten filament. The filament is heated to above $2000 \text{ }^\circ\text{C}$ by the filament current, which allows the electrons to freely escape from it (Arcam AB 2014). The emitted electrons are accelerated in an electrical field, obtained by applying a high voltage of $\sim 60 \text{ kV}$ between the filament and the anode, and then focused by means of an electromagnetic coil (focusing coil). The focused electron beam is selectively scanned over the powder bed with a layer-by-layer process directed by an EBM Control 3.2 software.

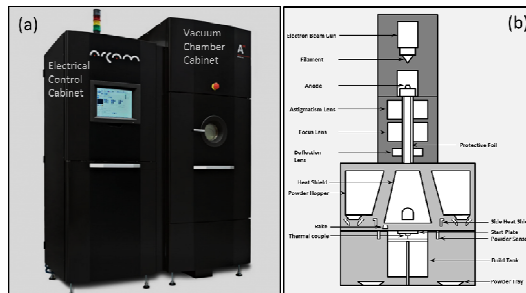


Figure 1. (a) Arcam A2XX EBM system. (b) Schematic view of an EBM system.

Ti-6Al-4V ELI (Grade 23) powder (Batch No. 877) supplied by Arcam AB was used for fabricating the impeller. ELI refers to as “Extra Low Interstitials”, which enables improved ductility and better fracture toughness for the fabricated builds (Arcam AB 2014). The powder size distribution ranges from 45 to $100 \mu\text{m}$. This limit on the minimum particles size ensures safe handling of the powder (Arcam AB 2014). The nominal composition of as-supplied powders is $6.0\text{Al}-4.0\text{V}-0.03\text{C}-0.1\text{Fe}-0.1\text{O}-0.01\text{N}-<0003\text{H}$ and Ti Bal. (wt.%). Recycling of non-melted and/or sintered powder was achieved via the powder recovery system (PRS) and a vibrating sieve (mesh size $\leq 150 \mu\text{m}$). All powder involved in the fabrication of EBM builds (both in the build tank and on the powder table) will be first passed through the PRS in which Ti-6Al-4V powder is used as a blasting medium, to break up sintered blocks of powder collected from the previous build under a pressure of $\sim 6 \text{ bar}$. Powder recovered from the PRS is sifted by using the vibrating sieve before

being mixed with any powder remaining in the two powder hoppers or new powder. All industrial parts built in this work were fabricated using powder recycled in this way.

There are three softwares used for creating and running builds on the EBM machine, namely, Magics, EBM Build Assembler and EBM control. The detailed work flow for generating a build via these three softwares will be given in the following section. Moreover, three build themes were involved in this work, i.e. Ti6Al4V-PreHeat-50um, Ti6Al4V-Wafer-50um and Ti6Al4V-melt-50um. These process settings were identified by Arcam AB to achieve optimal building results. Contour melting and in-fill hatching melting are included in the melt theme. Contour melting consists of two steps: outer contouring and the subsequent inner contouring. In particular, outer contouring should be more important because it may determine the building of thin parts. Here, a beam melting current of 4 and 10 mA, a focus offset of 0.29 and 0.25 mA, and a beam speed of 340 and 800 mm/s were used for outer and inner contouring, respectively. In addition, a current of 15 mA, a focus offset of 3 mA and a beam speed of 4530 mm/s were used for hatching. A 10 mm-thick stainless steel start plate could start to be heated by the electron beam when a pressure of $\sim 5 \times 10^{-4}$ mBar within the build chamber is achieved. Once a bottom temperature of 730 °C is reached, parts are built directly onto the preheated (a surface temperature of 850 °C) start plate by selectively melting layers of 50 μm under a controlled vacuum in the temperature range of 650-700 °C. The entire building process was kept under vacuum at $\sim 2 \times 10^{-3}$ mBar, controlled by using high-purity helium as regulating gas in order to prevent powder charging.

RESULTS AND DISCUSSION

Figure 2 illustrates the work flow for preparation of the impeller build file. Magics software was mainly used for fixing the part and creating supports if they are necessary. Figure 2a shows the STL file of impeller exported from Magics. The STL file was sliced into 2D compressed layer file (ABF file) with a thickness of 0.05 mm by using EBM Build Assembler software as shown in Figure 2b. Only ABF file can be imported into the embedded EBM Control software for additive manufacturing in Arcam A2XX machine. It is noted that each prepared build file should be simulated by using EBM Control software before starting a job. EBM Control software simulation results real that the impeller job will be completed within ~ 5 hours.

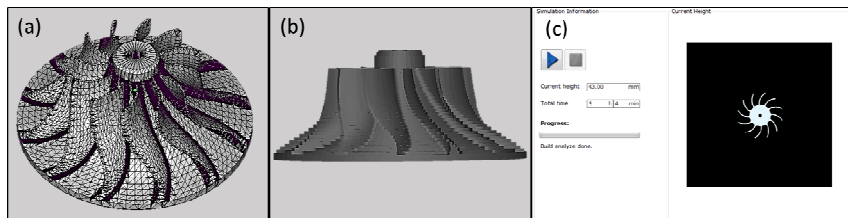


Figure 2. Work flow of file preparation for the impeller job (a) STL file exported from Magics software. (b) Illustrated ABF file showing the sliced structures after EBM Build Assembler software. (c) Simulation results by EBM Build Control 3.2 software.

During the EBM building process, various problems occurred, which resulted in failures of the impeller job. Figure 3a shows the appearance of numerous metallization on the inner surface of the heat shield after some builds. Due to high vapor pressure of some alloying elements at high temperature under vacuum as well as spraying of melted powder during manufacturing,

metallization would form on the inner surface of heat shield continuously at elevated temperatures. Furthermore, two kinds of metallization could be distinguished in Figure 3a. Metallization coating, which results from vapor of some alloying elements, was firmly overlaid on the surface of heat shield. The spraying of melted powder will give rise to the formation of metallization strips. Many metallization strips were found to fall off onto the start plate and powder table during heating process (Figure 3b). These metallization strips are fatal for the subsequent building process, because they will severely disturb the raking of powder. As the rake blades of Arcam EBM machine are extremely sensitive during the raking of powder, it is found that even a small disturbance caused by any foreign objects or even a small piece of sintered powder would result in a failure of the entire building. Thus, in order to avoid that any metallization coatings or strips peel off, very careful cleanliness of the heat shield and start plate will be performed before each start. In addition, it can be imagined that large amounts of metallization may result in the loss of some alloying elements in the build parts, which alternately affect their microstructure and mechanical properties. Therefore, metallization should be an important issue needed to be carefully taken into account during additive manufacturing of industrial parts by EBM.

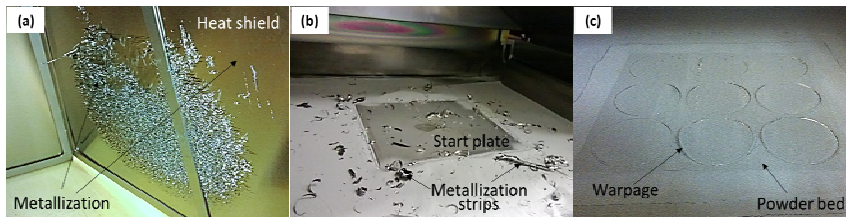


Figure 3. (a) Two kinds of metallization formed on the inner surface of heat shield. (b) Plenty of metallization strips peel off onto the start plate and powder table. (c) Warpage of some building parts.

Warpage of thin plates (usually <2 mm) at the initial dozens of building layers is another technical problem that commonly took place during the impeller fabrication by EBM. As seen in Figure 2, the impeller has a circular base with relatively large area. Figure 3c exhibits a suspended build job of 9 impellers with a base diameter of 50 mm. It is clear that some parts have severely warped at a thickness of ~ 1 mm. It can be easily understood that warpage occurs due to the nonuniform thermal stresses and residual stresses inside the building parts, which is attributed to the uneven heat distribution on the surface of start plate. It is worth noting that the build parts located at the front side of start plate, closing to heat shield window, are more easily to warp. That may be due to the fact that some heat could transfer towards outside through the heat shield window. A build temperature of $650\text{--}700$ °C was maintained during the entire EBM building process, which effectively release the residual stresses inside the as-melted parts. The effects of build temperature on microstructure and mechanical properties have been investigated. It is reported that lower build temperatures will result in poor sintering, charging of powder particles, and repulsion. By contrast, higher build temperatures will lead to part “swelling”, causing problems with powder raking and component distortion (Al-Bermani et al. 2010). In addition, a crossing in-fill hatching strategy was adopted, i.e. the direction of electron beam movement is rotated by 90 deg along z-axis every layer and the beam hatches at the same direction every 200 μm repeatedly. This strategy also aims at reducing the residual stresses accumulation inside the as-deposited materials. However, warpage would also frequently take place during building a component with a large cross-section area at initial stage. Moreover, the components with square geometries were found to be prone to

warpage. Concerning the exact geometry and area dependence of warpage, a more detailed experimental work combined with simulation is still needed in the future. Based upon our current experience, circular or complex-shaped parts with thin walls are preferable to square geometries when using EBM additive manufacturing. In order to avoid warpage, six symmetrical cylinder holes were extruded into the base of the impeller file. Moreover, some wafer supports were added to the down-facing surfaces. Figure 4 shows the industrial impeller that has been successfully built by our EBM machine, with a base diameter of 100 mm and a height of 43mm. The thinnest part in the impeller can be 0.8 mm. Its total build time is around 8 hours, which is much longer as compared to the simulation time obtained through the EBM Control. The extra time should be due to the raking of powder and the regulating of powder layer by the rake. Nevertheless, EBM has provided a high building rate mainly due to its Multi Beam feature. The evaluation of surface finish, microstructure and mechanical properties of the built impeller will be the next work.



Figure 4. Photograph of the built impeller by using EBM

“Swelling” was found to occasionally occur at sharp corners. Once warpage or “swelling” occurred, a building job must be stopped immediately. Otherwise, the rake will interfere with the warping region, which would eventually cause the failure of the build. A more serious problem is that a “smoke” phenomenon will often take place by fetching too much powder due to the uneven raking. The occurrence of “smoke” will enable much Ti-6Al-4V powder travel upwards into the drift tube and grid cup along the EBM column, which leads to frequent arc trips during building process. Several build failures occurred because of serious arc trips in our trials.

CONCLUSIONS

In summary, an impeller was successfully fabricated by using EBM additive manufacturing technique. EBM was found to be very suitable for building the circular or complex shapes with thin walls. It is indicated that metallization peeling-off, warpage, “swelling” and arc trips are the main reasons resulting in the failures of building jobs. However, these undesirable phenomena could be completely avoided when the following aspects have been paid close attention to: a thorough cleanliness of the entire EBM system before start, a reasonable placement of builds on the start plate, an optimized design on geometries, and so on. It needs to be mentioned that this work is based on some initial service experiences of the EBM machine. Nevertheless, it is believed to give a good guideline for our following work on EBM additive manufacturing.

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