Thermographic In-Situ Process Monitoring of the Electron Beam Melting Technology used in Additive Manufacturing

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ABSTRACT

Oak Ridge National Laboratory (ORNL) has been utilizing the ARCAM electron beam melting technology to additively manufacture complex geometric structures directly from powder. Although the technology has demonstrated the ability to decrease costs, decrease manufacturing lead-time and fabricate complex structures that are impossible to fabricate through conventional processing techniques, certification of the component quality can be challenging. Because the process involves the continuous deposition of successive layers of material, each layer can be examined without destructively testing the component. However, in-situ process monitoring is difficult due to metallization on inside surfaces caused by evaporation and condensation of metal from the melt pool. This work describes a solution to one of the challenges to continuously imaging inside of the chamber during the EBM process. Here, the utilization of a continuously moving Mylar film canister is described. Results will be presented related to in-situ process monitoring and how this technique results in improved mechanical properties and reliability of the process.

Keywords: Additive manufacturing, Electron-Beam Melting, Thermography, IR Imaging, Porosity

1. INTRODUCTION

Additive manufacturing, also known as 3D printing, is the formation of three-dimensional parts through a process of laying down one layer at a time and then fusing the next layer on top of the previous one. The building of a part in this manner greatly reduces the amount of wasted material and allows for very complex shapes. Additive manufacturing is an excellent choice for the production of models, prototypes, small production runs, and parts where the complexity prohibits the cost effective production by other means. There are several different techniques used in 3-D printing including; Fused deposition modeling[1] (FDM), electron-beam melting[2, 3] (EBM), selective laser sintering[4, 5] (SLS), and Laminated object manufacturing[6] (LOM). This paper discusses Thermographic observations of the EBM process.

The EBM process, as developed by ARCAM in Sweden[7], typically occurs in an unheated vacuum chamber, also known as the build chamber (see vacuum chamber in Fig. 1). At the top of the chamber is a computer controlled electron gun with sufficient current to melt the selected metal powder. The final part will be constructed layer-by-layer on the build platform that is located in the floor of the vacuum chamber. This platform is capable of being lowered in small increments, which will become the layer thickness during the build process. At the start of the process, this platform is lowered about 50 micrometers, and a layer of metal powder is raked across the floor of the chamber, filling the space above the build platform. An unfocused, low current electron-beam then uniformly pre-heats this layer of powder to a temperature slightly below the melt temperature of the powder. During the pre-heating phase the metal powder will weakly sinter together, holder the individual particles in place during the subsequent melting step. The pre-heat step is followed by the melting step wherein a high current focused electron-beam draws the pattern of the first layer of the part on the metal powder bed. This step only melts the powder directly under the electron-beam. The molten metal is held in place by the surrounding sintered powder and solidifies quickly. The build platform is then lowered allowing for the next layer of powder to be raked across. The process of lowering the platform, raking powder, pre-heating and melting continues until the part is completed. When the chamber is opened, the part is embedded within a sintered block of powder. This block of material is placed inside a grit blaster, which uses the same metal powder as the blasting media. The surrounding sintered powder is easily removed leaving the final part. The removed sintered powder is captured, filtered and recycled for future parts.

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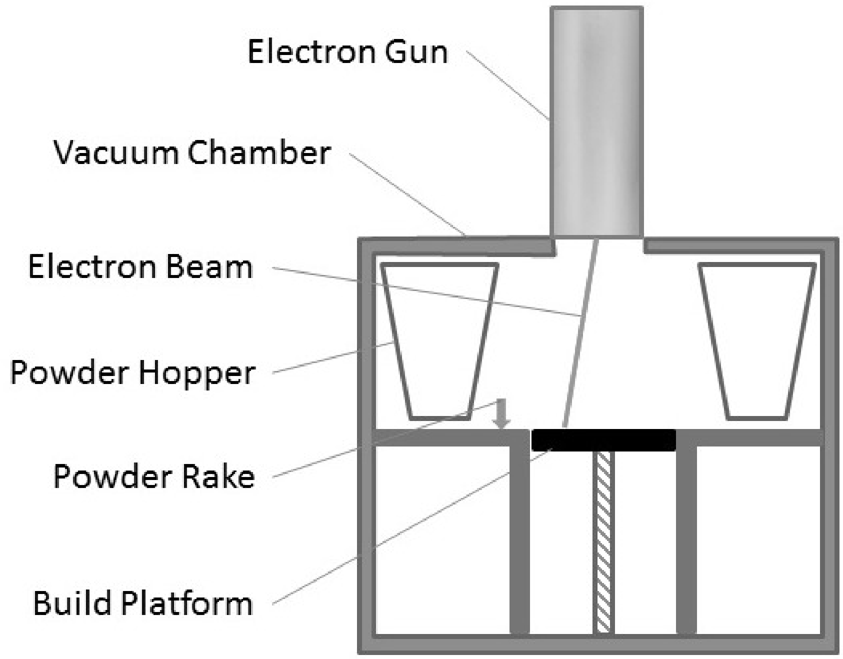


Figure 1. Schematic diagram of the ARCAM Electron Beam Melting system.

Currently, the EBM process is in open-loop process relying on process modeling coupled with trial and error to determine the appropriate settings of the processing parameters such as: beam focus, current level, beam sweep speed and acceleration. Since EBM is primarily a fast thermal process, it makes sense to monitor the process with a high-speed infrared camera. The IR camera is able to quantify the beam focus size, detect porosity and study the beam-powder interaction. Eventually an IR camera may become an integral part of a closed-loop feedback system designed to maintain part quality during the build. The current state-of-the-art process control relies on a complex set of semi-empirical equations to determine the optimum E-beam parameters. These equations depend on the properties of the metal powder bed, the geometry of the part being made and the location of other parts in the build space. Complex models have been developed to explain and predict the thermal behavior of the EBM process[8, 9]. Precise temperature measurements of the powder bed, solid parts and melt pool during the EBM process would be very useful in process control as well as model verification and development. However, before these measurements can be made, several challenges must be overcome to continuously image inside the chamber during the EBM process.

In order to implement Thermographic process-monitoring technologies, imaging must be performed through one of the two existing viewing ports in the vacuum chamber. Unfortunately, there are free metal ions released from some metal powders during the build process, and deposition of these ions will coat and opacify an unprotected view port window. ORNL has developed a shutterless system based on a sacrificial moving Kapton film to protect the window. A film canister mounts in the existing view port on top of the build chamber (located between the electron gun and the chamber door). A roll of Kapton film is under vacuum within the canister and stops any metal build-up on the Quartz glass view port. Importantly, a piece of leaded glass is positioned over the quartz window to block x-ray emissions. Lead tape is used around the outside edge of lead glass to block x-rays from escaping. This shutterless viewing system allows continuous IR imaging of the electron beam interaction with the metal powder bed. A second view port is located in the chamber door and is equipped with a mechanical shutter. However, this view port can only be used for a limited time with low melting point powders due to interior metallization.

2. EXPERIMENTAL SET-UP

2.1 Viewing through a shutter protected window

The ARCAM systems are equipped with a window in the front access door. A manually operated mechanical shutter protects this window from metallization on the interior surface due to evaporation or sputtering of the lighter elements in the metal powder. This window is typically used to adjust the E-beam during set-up and to periodically monitor the progress of the build. The fastest and easiest approach to infrared imaging inside the build chamber is to aim the IR camera through this window. However, while the shutter is open, some level of metallization occurs, resulting is reduced transmission through the window as a function of time. This makes calibration for temperature virtually impossible and limits the amount of time during which the build may be observed. This position also has the IR camera at a shallow angle to the powder bed, making spatial measurements challenging and preventing a sharp focus from front to back (see Figure 2). This image was taken with an unfiltered 50 mm lens on a FLIR[10] SC-8200 midwave IR camera with an integration time of 1.0 ms. The front area of this image is in focus, but the rear is out of focus due to the limited depth of field of the lens. Also visible in the image are several "comet-like" bright dots with bright tails. These dots are the E-beam showing up in various different locations during the 1ms exposure of the IR camera. The window became too opaque for imaging 3 minutes after this image was acquired due to metallization build-up on the inside. In order to over come the metallization of the window, a shutterless window protection system was developed.

Figure 2. IR image acquired through the window in the front access door of the ARCAM system.

2.2 Viewing through a film protected window

In order to protect the inside of the window from metallization, a film-based system was developed (see Figure 3). A thin Kapton film is spooled across the vacuum side of the window during the E-beam melting process. With each new layer of the build a new area of Kapton film is positioned in front of the window, while the partially metalized area of the film is spooled onto the film take-up reel. The Kapton film based shutterless window system was originally designed similar to the windows used on the front door; A thick disk of quartz, due to the high vacuum inside the chamber, and a thick disk of leaded glass to eliminate X-rays produced when the E-beam strikes the metal powder. While imaging of the high temperature EBM process is possible through these 2 thick pieces of glass, the dynamic range of the images is relatively low due to the extremely low transmission of each of these windows. The 9.8 mm thick Quartz window has an infrared transmission (3-5 μm) of 0.324% while the 10.1 mm thick Leaded glass window has an infrared transmission of 1.08%. The 60 μm thick Kapton film has an infrared transmission of 78.7%. The combination of the 2 windows and

Kapton film, back-to-back, results in a window system with a transmission less than 0.0028%. In order to increase the infrared transmission of the window system the Quartz window was replaced with a 2 mm thick Sapphire window with an IR transmission of 86.3%. This window system now has a transmission of 0.73%, resulting in a much larger dynamic range in the thermal images.

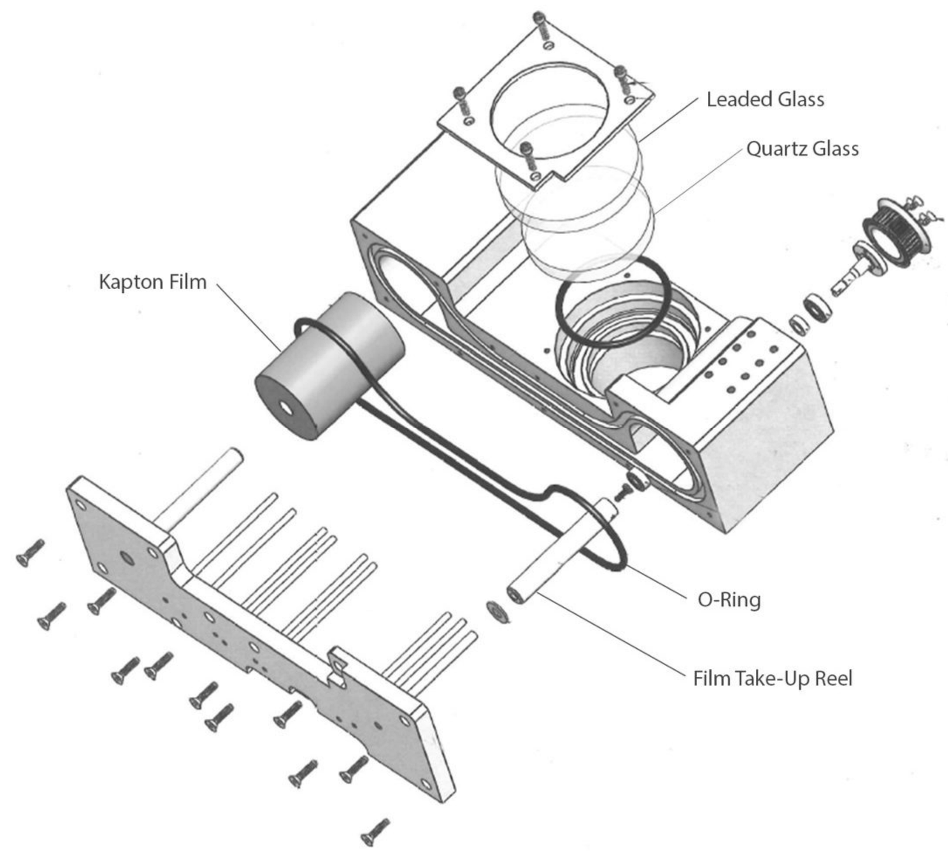


Figure 3. Exploded schematic view of the Kapton Film based shutterless window protection system.

2.3 Viewing through a mirror protected window

An alternate approach currently under development at ORNL is a single mirror periscope as shown in Figure 4. The periscope sets over a second view port on the top surface of the ARCAM vacuum chamber. The interior of the periscope is open to the build chamber and forms a vacuum seal with the top of the chamber. A mirror directs the Field-of-view of the IR camera down into the build chamber and eliminating the limited depth of field issue from the first port. The only other optical element between the IR camera and the powder bed is a sapphire window to allow imaging into the vacuum system. This system eliminates the need for the Kapton film since the window is no longer in the line-of-sight of the powder bed. The first surface aluminum mirror is subject to metallization, but the metalizing element is typically aluminum, so the effect on the reflectivity is minimal compared to the presence of the Kapton film. The as-received aluminum mirror has an IR reflectivity of 97.8%. Once the mirror has undergone 12.5 hours of metallization due to exposure to the build environment, the reflectivity only drops to 43.0%. The leaded glass is eliminated as a result of the non-line-of-sight optical path. X-rays generated as a result of the electron beam interacting with the metal powder bed are absorbed in the metal body of the periscope above the opening to the build chamber.

Thus the optical path of the periscope has an effective transmission of 37.1%, or two orders of magnitude greater than the film-based shutterless system described above.

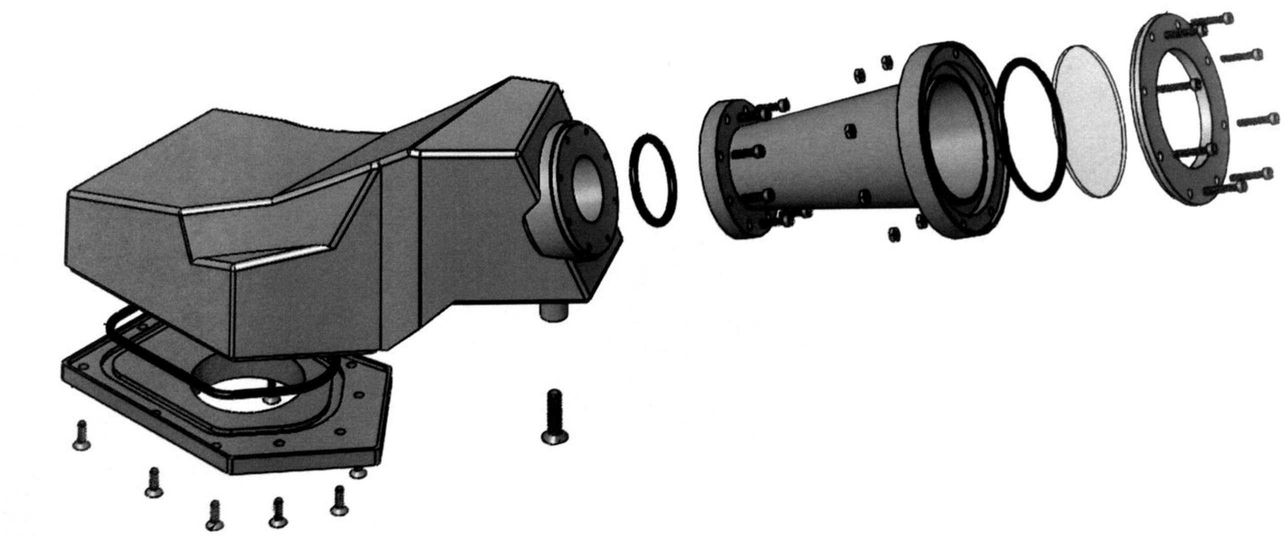


Figure 4. Drawing of the mirror based window protection housing. A mirror located above the vacuum chamber opening directs the image through a Sapphire window located out of the line-of-sight of metallization atoms and X-Rays.

3. RESULTS

Now that it is possible to obtain high-speed IR imaging during the EBM process, several new research and development paths are open. These include, but are not limited to, automated beam focus during set-up, observation of unwanted melting during the pre-heat phase, porosity detection, and temperature measurement for model verification.

3.1 E-Beam focus measurement

The E-beam focus parameter is very important to the heating of the powder bed, since it is this parameter, coupled with current and speed, which controls the energy deposited per unit area and thus the resulting temperature. A spatial calibration can be performed on the system, which then allows the measurement of distances and speeds during the build. One useful measurement is the width of the E-beam during the pre-heat stage of the process.

Figure 5a shows an IR image taken during the pre-heat phase. A spatial calibration is applied to the image by using the known size of the square located in the upper right corner. This square is 20 mm by 20 mm and is represented by 269 pixels in the image. The E-beam's heat affected zone, showing up as two bright lines across the image, are each 23 pixels wide (top-to-bottom) resulting in an E-beam focus width of 1.71 ± 0.07 mm. The E-beam width during melting can also be measured. As shown in Figure 5b, the E-beam is measured to be 0.8 mm during the melting phase.

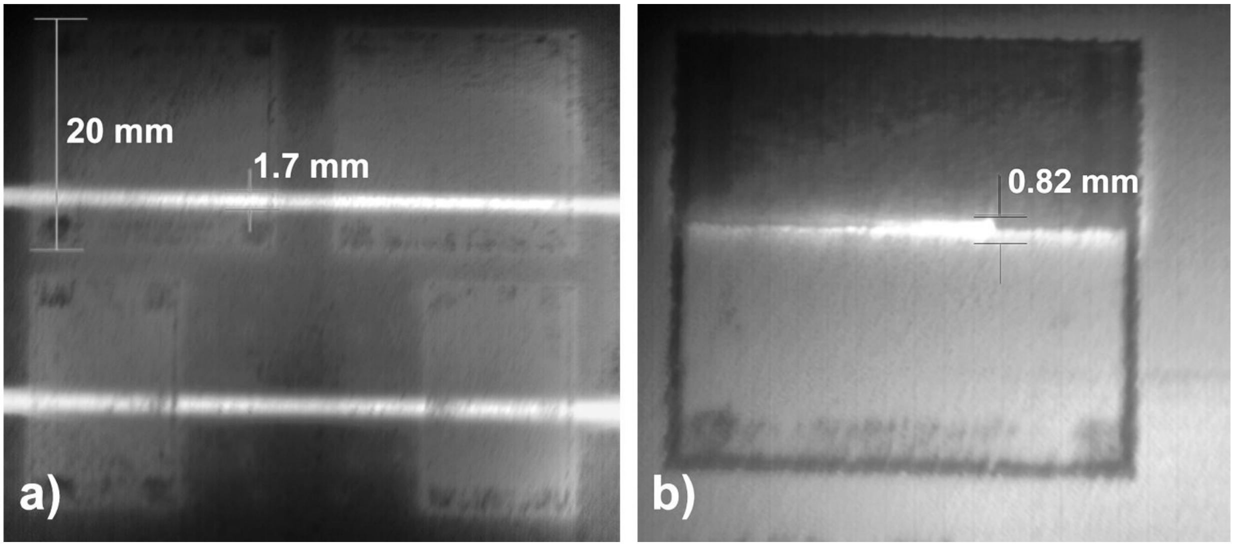


Figure 5. Measurement of the E-beam width, a) during pre-heat and b) during melting. In b) the upper portion has already been melted with the e-beam raster.

3.2 Over Melting during pre-heat

It is clear from the images that the melted regions appear darker (cooler) than the powder bed, even though the melted regions are obviously hotter. This is due to the powder bed having a higher emissivity than the highly reflective surface of the resulting fused metal part region. This allows easy detection of molten regions, even without the benefit of a temperature calibration. As discussed earlier, the powder bed is pre-heated with a defocused E-beam to partially sinter the powder bed. During this phase of the process it is not expected or desired for the powder bed to become molten. However, in some cases melting has been observed during the pre-heat phase. Figure 5a shows melting during the pre-heat, particularly in the corners of the square blocks and along the block edges. This overheating can result in localized swelling of the part, which may lead to dimensional flaws, ultimately resulting in rejection of the part for service. Continuous monitoring using an IR camera can help with the early identification of manufacturing conditions and defects, which affords the opportunity to make immediate changes to assure final part quality.

3.3 Porosity detection

Continuous IR camera monitoring can also contribute to the important area of porosity detection. If porosity can be detected during the build process, then adjustments to the process parameters can be made to eliminate or enhance further porosity production, whichever is desired. Generally speaking, porosity is regarded as undesirable. Porosity can occur when powder is ejected from the bed by the E-beam or if the energy deposited by the E-beam is not great enough to cause melting. The latter case is commonly observed in the first few layers of an overhang structure. When the part design calls for powder to be melted, the amount of energy required depends partially on the material below the powder. More energy is required if the layers below the melt pool is solid metal. This is due to the fact that solid metal possesses a relatively high thermal conductivity and thus, acts as a heat sink. If, however, the material below the area of interest is unmelted powder, then the energy required is significantly lower due to the lower thermal conductivity of the powder bed. This sudden step change in energy deposited per unit area is most often accomplished by increasing the beam speed. A thermal support structure can be added to assist in improving the thermal conductivity of the powder bed below an overhang structure. This thin and fragile support structure can be easily removed after processing. A series of test blocks containing overhangs with various thermal support structures were designed and printed (see Figure 7). Three different support structures were designed to test their relative effect on the resulting overhang. As seen from top to bottom in Figure 7b, these structures are referred to as “Cross,” “Hex” and “Line.” Each layer of the build was 0.05 mm thick. In addition to the different thermal support structures, two different values were used for Focus Offset (FO) parameter.

Focus Offset is a numerical value representing the sharpness of the E-beam focus, where a FO =0 is perfectly focused to a point and a value around 300 would be used for pre-heating.

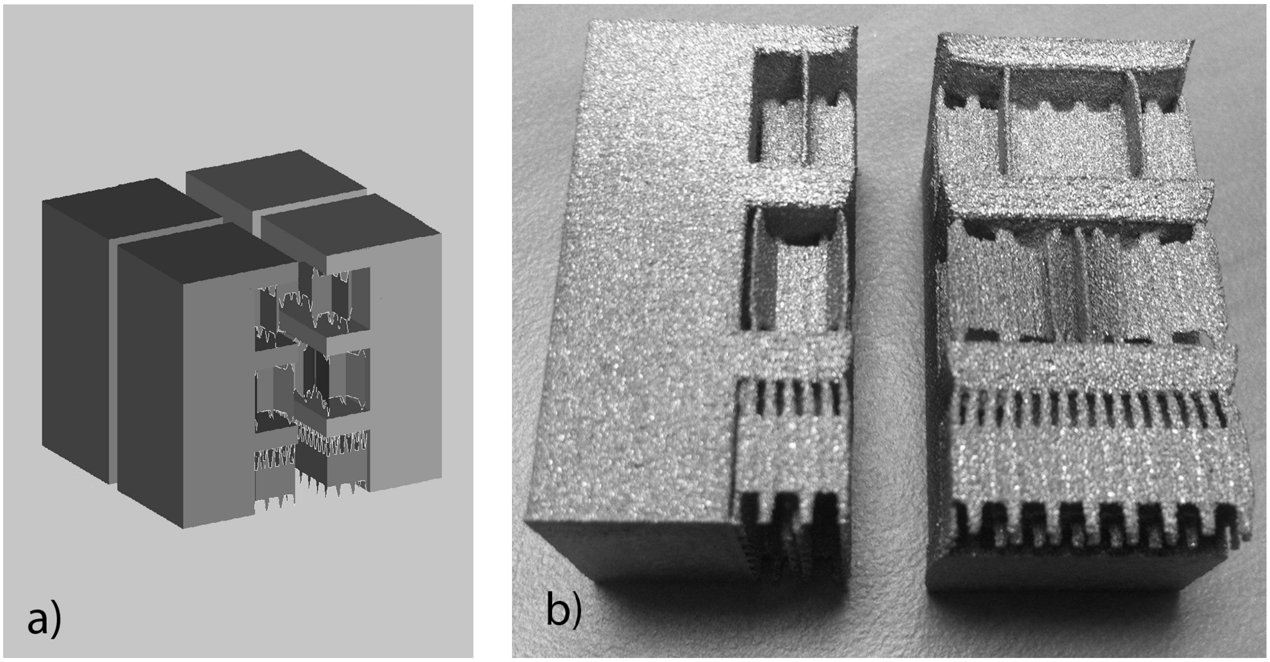
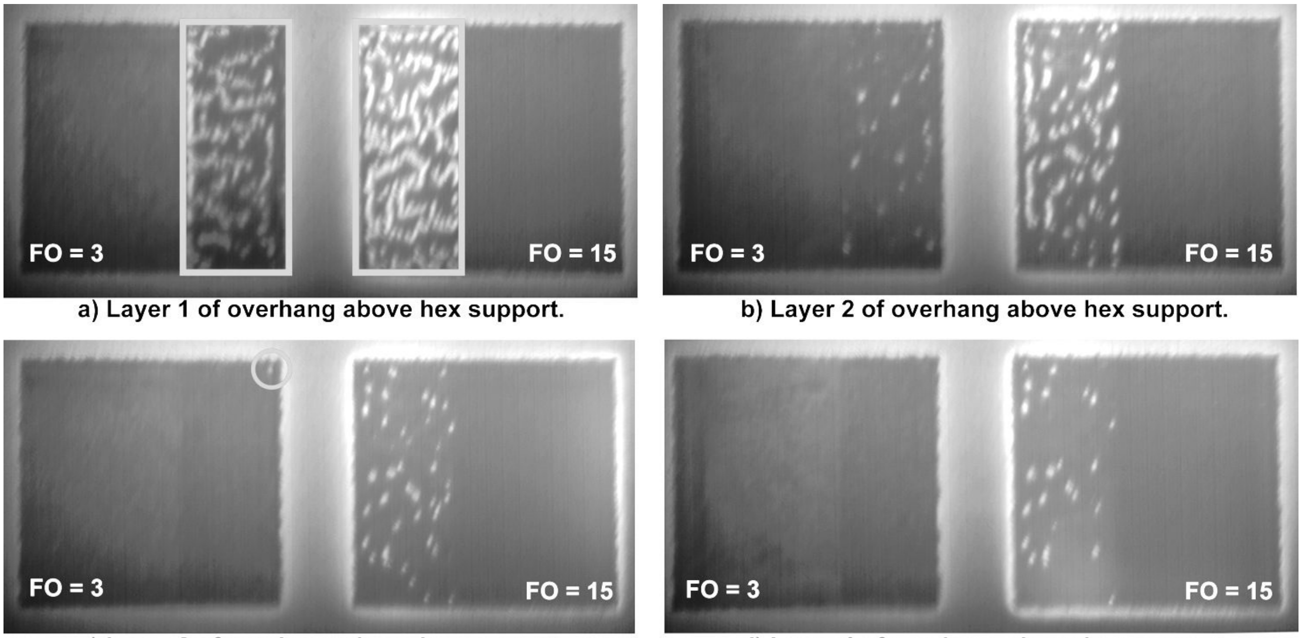


Figure 7. Test blocks containing overhang structures with their thermal support structures, a) CAD design of the test blocks and b) resulting test blocks printed out of metal.

Figure 8 shows the thermal imaging results for the first four layers of the overhang structure above a hex thermal support structure. The red rectangles in Figure 8a indicate the region of the overhang. The left block in each image was made using a Focus Offset value of 3, while the block on the right is produced using an FO value of 15. The bright features within these overhang regions are believed to be porosity (i.e., regions of unmelted powder). The E-beam is observed to sweep faster across these overhang regions as discussed above. The porosity in the left block appears to be dimmer because this block was produced a few seconds before the block on the right and therefore had this additional time to cool. While the difference in porosity level is not easily discerned by eye for the first layer of the overhang produced with FO=3 and the overhang produced with FO=15, this difference is clearly visible by the second layer (Figure 8b) as the overhang produced with FO=15 possesses significantly more porosity than the overhang produced with FO=3. Figure 8c shows that by the third layer only one pore is visible on the overhang produced with FO=3, while nearly 40 pores remain on the overhang produced using FO=15. Porosity no longer forms in the overhang produced with FO=3 by the fourth layer as shown in Figure 8d, while there remains nearly 2 dozen pores in the overhang produced with FO=15. In fact, the porosity was not completely eliminated from this overhang until layer 10.

4. FUTURE WORK

The most immediate need for this project is to develop a temperature calibration, which may be applied to the infrared images. This would allow the temperature measurement of the powder bed during pre-heat and of the melted surfaces of the produced parts. This information can then be used for model verification and refinement. In addition, it is planned to feed this information back to the program controlling the E-beam, so that E-beam parameter can be adjusted to eliminate pre-heat melting and porosity formation during melting.



a) Layer 1 of overhang above hex support.
b) Layer 2 of overhang above hex support.
c) Layer 3 of overhang above hex support.
d) Layer 4 of overhang above hex support.

Figure 8. Porosity is detected as bright regions or spots.

5. CONCLUSIONS

Two shutterless systems are under development at Oak Ridge National Laboratory in order to allow continuous infrared monitoring of the E-beam melting process. The first system involves the use of a translating Kapton film to protect the window from metallization. This system as been successfully demonstrated and has an effective transmission of 0.73% in the 3 to 5 micron spectral band of the IR camera. The second system is a single mirror periscope with an effective IR transmission of 37.1%. The continuous IR monitoring of the EBM process allows the observation and study of various important phenomena useful in understanding and improving the process. The heat-affected area of the E-beam may be measured and focused quantitatively, instead of "by eye" as is the common accepted practice at present. It has also been demonstrated that porosity can be detected using an IR camera. This porosity is revealed as bright features on the dark background of melted metal. The effect of E-beam focus on the production of porosity in overhang regions has also been studied. The small change in Focus Offset from a value of 3 to a value of 15 has a large effect on the amount and depth of porosity in overhang regions. Another important observation is that, under certain conditions, melting can occur during pre-heating. The premature melting causes overheating and localized swelling, which in turn, results in geometric flaws and inconsistencies. It is anticipated that in the future the image analysis software can quantize such observations and fed back to the E-beam control software to maintain part quality.

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