Control Methods for the Electron Beam Free Form Fabrication Process

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Abstract

Engineering a closed-loop control system for an electron beam welder for additive manufacturing is challenging. For earth and space based applications, components must work in a vacuum and optical components must be protected from becoming occluded with metal vapor. For extraterrestrial applications added components increase launch weight and increase complexity. Here we present three different control methods for electron beam free form fabrication. A relatively simple coarse feedback control method is introduced that couples path planning and electron beam parameter controls into the build process to increase flexibility and improve build quality. The different approaches may be applied separately or together to provide enhanced EBF^3 system performance.

Introduction

Researchers at NASA Langley Research Center have developed the Electron Beam Free Form Fabrication (EBF^3) process, a rapid metal deposition process that works efficiently with a variety of weldable alloys [1,2,3]. The EBF^3 process can be used to build a complex, unitized part in a layer-additive fashion, although the more immediate payoff is for use as a manufacturing process for adding details to components fabricated from simplified castings and forgings or plate products. Figure 1 shows a schematic of an EBF^3 system. The EBF^3 process introduces metal wire feedstock into a molten pool that is created and sustained using a focused electron beam in a vacuum environment (1×10^{-4} torr or lower). Operation in a vacuum ensures a clean process environment and eliminates the need for a consumable shield gas.

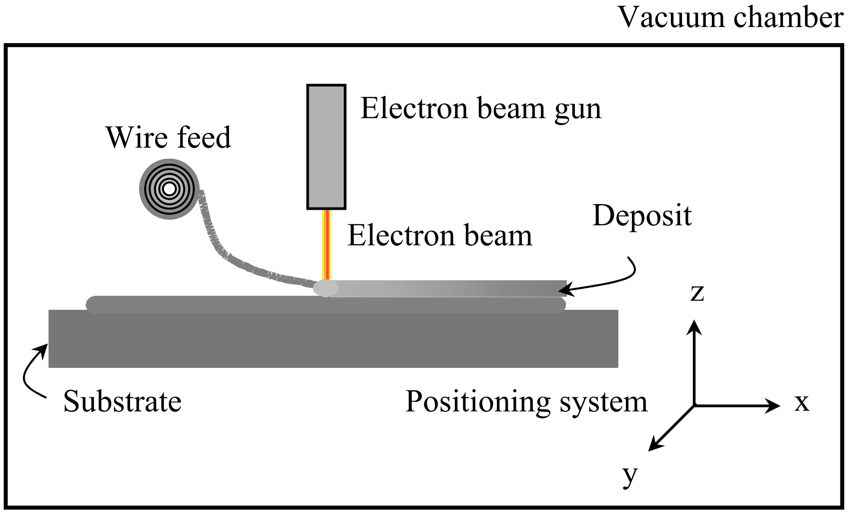

Figure 1. Schematic of electron beam freeform fabrication (EBF^3) system.

The EBF^3 process is nearly 100% efficient in feedstock consumption and approaches 95% efficiency in power usage. The electron beam couples effectively with any electrically conductive material, including highly reflective alloys such as aluminum and copper. A variety of weldable alloys can be processed using EBF^3; further development is required to determine if non-weldable alloys can also be deposited. The EBF^3 process is capable of bulk metal deposition at deposition rates in excess of 150 in^3 hr^{-1} as well as finer detail at lower deposition rates with the same equipment. The diameter of the wire feedstock is the controlling factor determining the smallest detail attainable using this process: fine diameter wires may be used for adding fine details and large diameter wires to increase deposition rate during bulk deposition. In a system with dual wire feed that can be controlled simultaneously and independently, the two wire feeders may be loaded with either a fine and a coarse wire diameter for different feature definition, or two different alloys to facilitate producing components with compositional gradients.

As with all new solid freeform fabrication processes, much of the control and selection of processing parameters for the EBF^3 process have been empirically derived. Better understanding of the process is required to enable development of an automated control system. Lessons learned and techniques developed for another metal deposition process, the Laser Engineered Net Shaping (LENS^{TM}) process, may be applicable to the EBF^3 process [5,6]. The LENS^{TM} closed loop feedback control was granted US Patent number 6,459,951, October 1, 2002, and describes a method using optical and thermal imaging to monitor the molten pool and deposition height to achieve a closed loop process. However, due to difficulties with controlling the mass flow rate of the powder and slow update rates of the lamp-pumped Nd:YAG laser in the LENS^{TM} process, control was established indirectly through translation speed control governed by the understanding of the effects of input process parameters on the thermodynamics (as indicated by the melt pool size and shape) and geometry of the deposit (as indicated by the bead height). The EBF^3 process offers many additional degrees of freedom in directly controllable variables as compared to that of the LENS^{TM} process, which permits development of a different closed loop control methodology and ability to achieve finer process control.

Control Methods

Input parameters for the EBF^3 process include beam power, beam pattern, travel speed, and wire feed rate. Variations in these parameters influence the deposit height and width (geometry), alloy composition (chemistry), residual stresses within the final part, and distortions of the final part. The input parameters have been shown to have coupled interactions that currently require trial and error, and expert human experience, to find desirable combinations. Even with a set of parameters that provide an acceptable deposit geometry, chemistry, etc., there is still some variability within the process to motivate the design of a closed-loop control system. This system would be able to monitor the build process, measure the variability, and correct the system as the build progresses.

There are three methods to consider for EBF^3 process control: feed forward, coarse feedback and fine feedback. Each of the three process controls is explained here along with their respective advantages and disadvantages. Since EBF^3 can be applied to industrial, low Earth orbit, and Lunar/Mars surface operations, design challenges for those applications are also discussed.

Feed Forward

The term "feed forward" is used to indicate that information about the deposition process is well known *a priori*. That is, the information only flows forward during the build process, there is no feedback. Figure 2 illustrates the steps used in the process. First, CAD (Computer Aided Design) software is used to define the part geometry. Second, CAM (Computer Aided Manufacturing) software is used to reduce the part definition into commands to build layers in the additive process. Third, the EBEAM step is used insert electron beam control parameters into the CAM file. Fourth, CNC (Computer Numeric Control), electron beam control parameters and tool path commands, are given to the electron beam welder to produce the part.

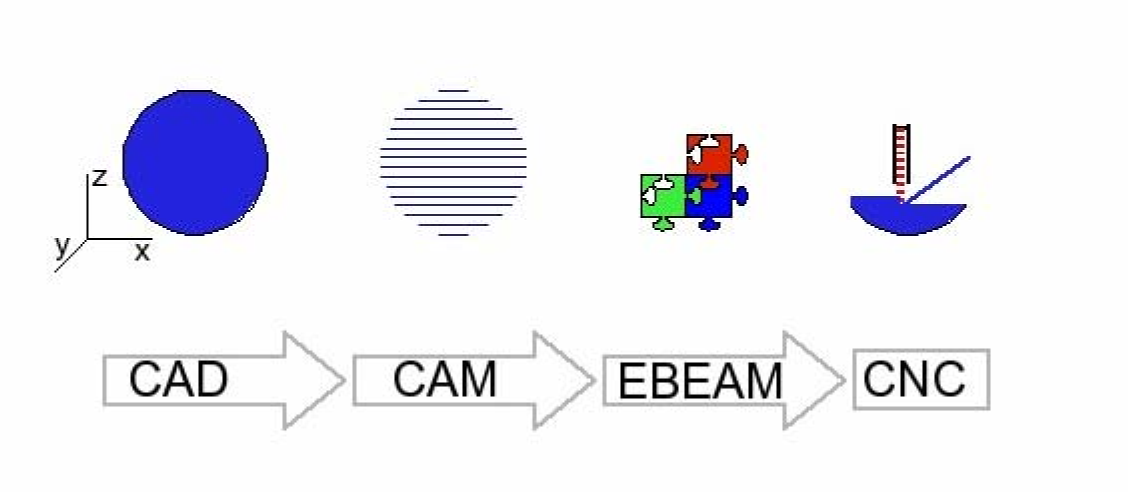

Figure 2. The classic approach used for subtractive manufacturing with an additional step, EBEAM, needed for EBF^3 additive manufacturing. The arrows represent a step-by-step process with information flow only in the forward direction.

The non-linear relationships between input parameters and their role in a deposits final chemistry was shown in a recent DOE (Design Of Experiments)[4]. Figure 3 shows travel speed and beam power each taken individually play a very small role in deposit chemistry. Collectively they play the second strongest role in characterizing the deposit chemistry indicating a strong coupling between these 2 input parameters on that particular output parameter.

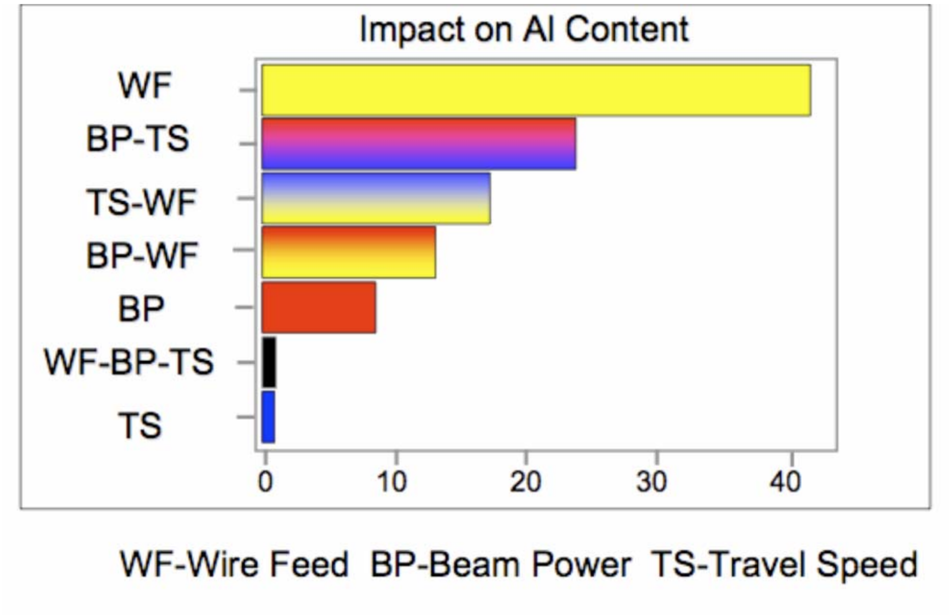

Figure 3. Design of Experiments results showing the complex interaction of wire speed, beam power, and travel speed and their impact on Aluminum chemistry in Ti-6Al-4V.

The main advantage of a feed forward process control is its apparent simplicity since the electron beam welder, as delivered from its manufacturer, needs no modification. A disadvantage to this method is that a human expert trained through trial and error must select the input parameter combination. Additionally, even with a good selection of electron beam control parameters, only a few simple parts have been built without operator intervention. That is, a human in the loop watches the build process and makes small adjustments to deposition parameters as the build progresses. Further, even with operator adjustments, errors may arise. Figure 4 shows a build with an errant corner. About 50 layers were deposited very consistently but near the end of the build, something changed and the small error on one layer became larger in subsequent layers. In other builds attempts have been made to correct problem builds with human intervention with varying levels of success.

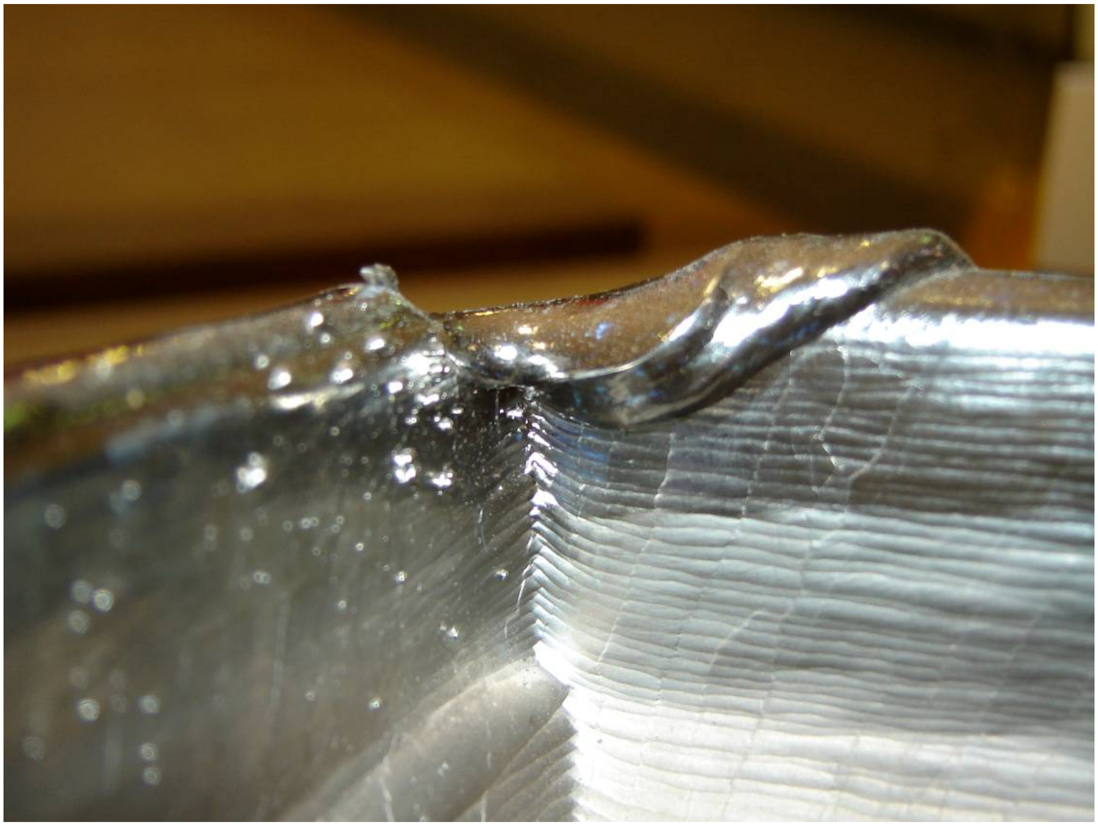

Figure 4. A build error after about 50 successful layers. A small error in one layer becomes larger in subsequent layers.

The feed forward method can be improved through experiments and DOE analysis. Data from those experiments would be used to quantify the relationships among the parameters and make it possible to capture that process knowledge into algorithms. These relationships need to be understood for the feed forward method, and for any other type of control method. Open loop deposition with human process control has been used to build a variety of different shapes, but repeatability and quality control is extremely difficult to achieve. The feed forward approach helps to improve the repeatability and build quality, but is unable to identify and correct errors, prevent propagation of errors, and ensure part accuracy.

Coarse feedback

Coarse feedback control is an intermediate step that closes the control loop, not at the level of real-time control, but a broader level. The steps from the classic CAD/CAM/CNC process are still used but a feedback path and a comparison function are added. In this method, the original part drawing is included in the control loop. Figure 5 shows the information flow. First, one layer is taken from the part definition (CAD) and used to generate a tool path (CAM). EBF^3 process parameter information is computed and added to the tool path and the welder (CNC) builds that layer. After one, or several layers (depending on tolerance requirements), the height profile of the deposit is taken. That height information is fed back into the system and is used to compute what layer height will be taken next from the CAD description. For instance, if a deposit bead height of 0.030 in. was assumed (based on feed forward experiments) but an average bead height of 0.025 in. was measured, the next layer from the CAD drawing will be taken from 0.025 in. above the previous layer. This 0.005 in. error, if propagated over 100 layers, results in a part that is 0.5 in. too small, resulting in a 20% scaling factor only in the Z (height) direction.

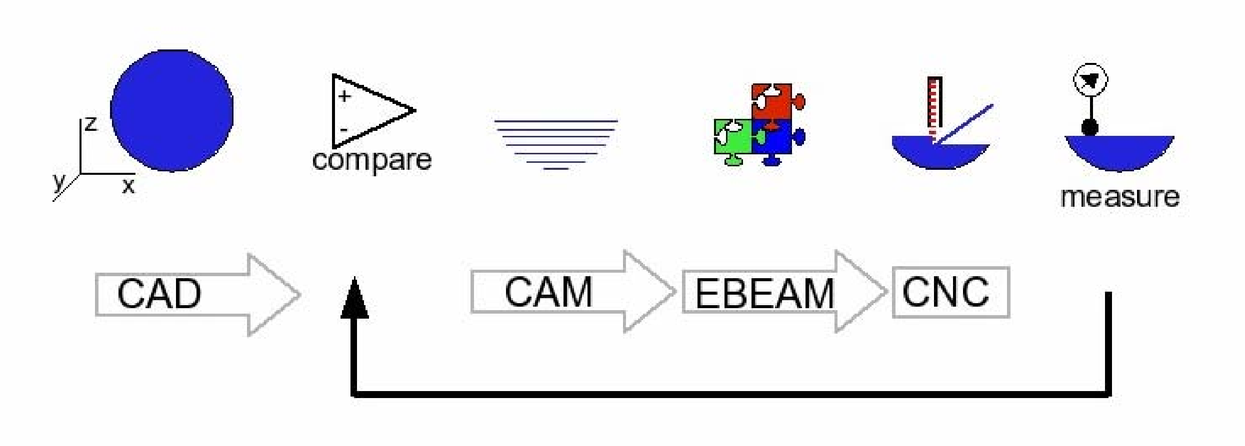

Figure 5. Adding a coarse feedback path to the feed forward approach. Here the direction arrows show a feedback path of information that will be used to plan the next layer of the build.

Corrections are not limited to layer height. If an error occurs and a depression is measured along the tool path, the coarse feedback loop can be used to modify the EBF^3 parameters for the next several layers until the depression is filled in. Additionally, corrections are not limited to height. Depending on the features of the post-build measuring system, if bead width can also be measured, corrections for bead width could also be applied.

Any corrections that must be applied still rely on a thorough understanding of how the EBF^3 parameters work in the feed forward method. For instance, a correction to bead height may not be a simple matter of tweaking one parameter over the measured distance. It appears necessary to tweak several parameters concurrently to affect the correct build geometry and chemistry. As such, it is not likely that a simple linear controller will control the EBF^3 process.

The main advantage of coarse feedback control is that it is a relatively simple developmental step from the feed forward method. Sensors and processing are needed to measure the build geometry, but these can be simple off-the-shelf measuring devices. Once geometry information is obtained, comparing that information with the CAD diagram is a straight forward process. Any equipment used to monitor the build must work in a vacuum and survive the metal vapor atmosphere. Since measuring can be accomplished while the electron beam is off, shutters can protect optical devices from metal vapor deposition.

The coarse feedback system offers several benefits for space based applications. First, additional equipment adds weight and directly influences launch costs; this method adds very little equipment. Second, even before launch, a simpler system is easier to integrate and test. Third, a simple system should require less time for maintenance, lower energy requirements, and be more reliable.

Fine feedback

Fine feedback incorporates sensors to monitor and correct the deposition process in real-time. Figure 6 shows the flow of information for this method. As with the feed forward and coarse feedback methods, the first steps are to take the CAD drawing, slice it into layers with CAM software, and merge the tool path information with EBF^3 control parameters. This method assumes that the feed forward information will yield a build that is relatively close to the desired geometry and chemistry and that any corrections will be relatively small. As the electron beam welder is depositing a layer, the process is closely monitored and information is immediately available for feedback. The measured process features are compared with the desired build geometry and an error signal is used to tweak the CNC controller.

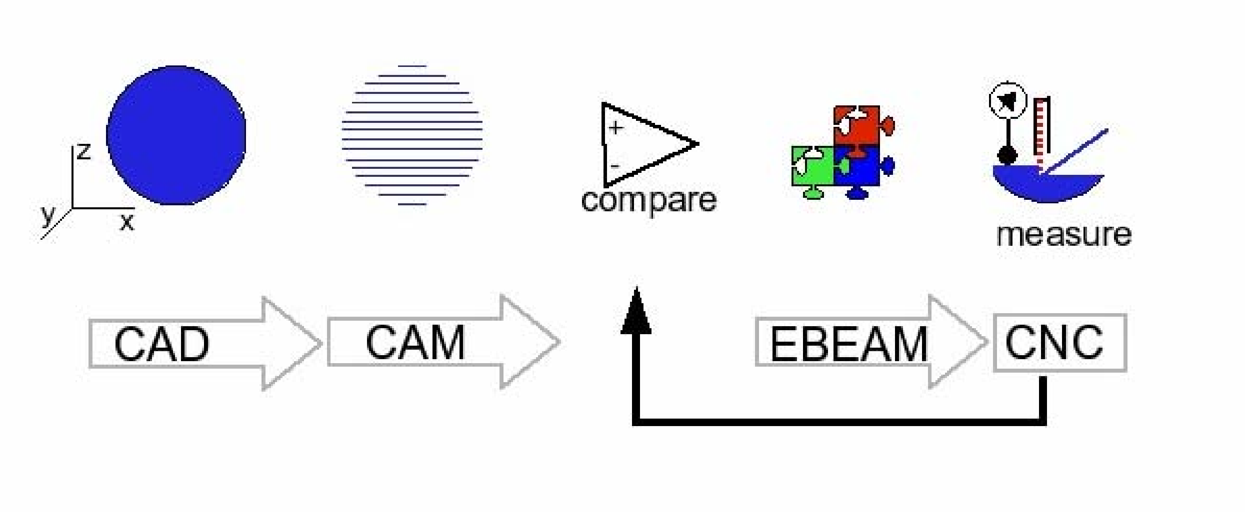

Figure 6. Adding a feedback path to the classic approach. Here the direction arrows show a feedback path of information that will be used to correct the CNC controls in real-time.
In comparison to the coarse feedback control the CAM information, or the layers of the build, are all computed once.

Melt pool temperature, melt pool geometry, and the height of the build are the likely parameters for monitoring the EBF^3 process. Direct observation of the melt pool reveals that as layers are added, residual heat from previous layers affects the melt pool geometry. Feedback to maintain a relatively constant temperature in the melt pool may affect the repeatability of the EBF^3 process from layer to layer (for geometry and chemistry).

Temperature and melt pool geometry are interrelated and monitoring temperature alone may be sufficient to obtain consistent metallurgy. Measuring the geometry of the melt pool has implications for how the wire is approaching the melt pool. As wire approaches the melt pool it begins to melt in the electron beam and then flows into the melt pool. The surface tension of the liquid metal allows a bridge to exist between the approaching wire and the melt pool. Monitoring the shape of this bridge is an indicator of whether or not wire is approaching the melt pool at a desirable height. Observation in Earth-g, Lunar-g, Martian-g, and 0-g, reveal that surface tension, and therefore maintaining this bridge, is critical to the build process. Image processing could be implemented to measure this bridge and provide a feedback signal to the circuit that controls the welder's Z height.

If melt pool temperature, melt pool geometry, and build height can be effectively measured and fed into the electron beam welder control system, another thing to consider is the response time of the electron beam welder components. The reaction times of the position motion axes, wire feed mechanism, and electron beam power, need to be assessed so that the control system design is stable.

The advantage of the fine feedback method is that feedback about the build process is almost immediate and should provide a very consistent build. For example, there should be almost no height variability at a given layer such that the next layer would need to be modified. Also, with close monitoring and control of the melt pool, the chemistry of the build should have a narrower range of quality. The additional monitoring and computing equipment adds complexity to the system, but the complexity may be worthwhile if it enables unattended operation, enables repeatable process control, and increases build quality. While the additional complexity may justify itself on the industrial shop floor, it has disadvantages that are more severe for space-based applications. As mentioned earlier, complexity adds to system weight, increases integration and test requirements, potentially increases maintenance requirements, and potentially reduces reliability. The weight of the associated measuring and computational systems required for achieving coarse vs. fine feedback control must be carefully examined to determine which approach provides the best trade-off between weight, complexity, and performance.

Summary

There are reasons for pursuing all three feed forward and feedback approaches. Serially they represent a development pathway from a simple method to more complex methods. First, understanding the complex relationships between the input parameters and building that understanding into algorithms broadens the application to more than just a limited number of successful parameter settings. This has implications not only for complex build geometries but also chemistry, residual stress, and distortion control. Second, adding a coarse loop control to the system appears to be a simple developmental step that can be accomplished with off-the-shelf hardware and relatively simple software. This developmental step also adds consideration for repair applications where the topographic features of part are measured and compared the original CAD drawing so that tool paths and EBF^3 parameters are issued to add missing material. Selection of successful EBF^3 parameters is dependent on work done for open-loop control. Third, adding fine loop control offers the possibility of higher quality control for geometry and chemistry, but with the cost of higher complexity. For some applications it may be beneficial to incorporate all three methods in unison, while others may derive adequate performance thru application of one or more methods discussed.

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