Control of Space-Based Electron Beam Free Form Fabrication

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Abstract

Engineering a closed-loop control system for an electron beam welder for space-based additive manufacturing is challenging. For earth and space based applications, components must work in a vacuum and optical components become occluded with metal vapor deposition. For extraterrestrial applications added components increase launch weight, increase complexity, and increase space flight certification efforts. Here we present a software tool that closely couples path planning and E-beam parameter controls into the build process to increase flexibility. In an environment where data collection hinders real-time control, another approach is considered that will still yield a high quality build.

Introduction

Researchers at NASA Langley Research Center have developed the electron beam freeform 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.

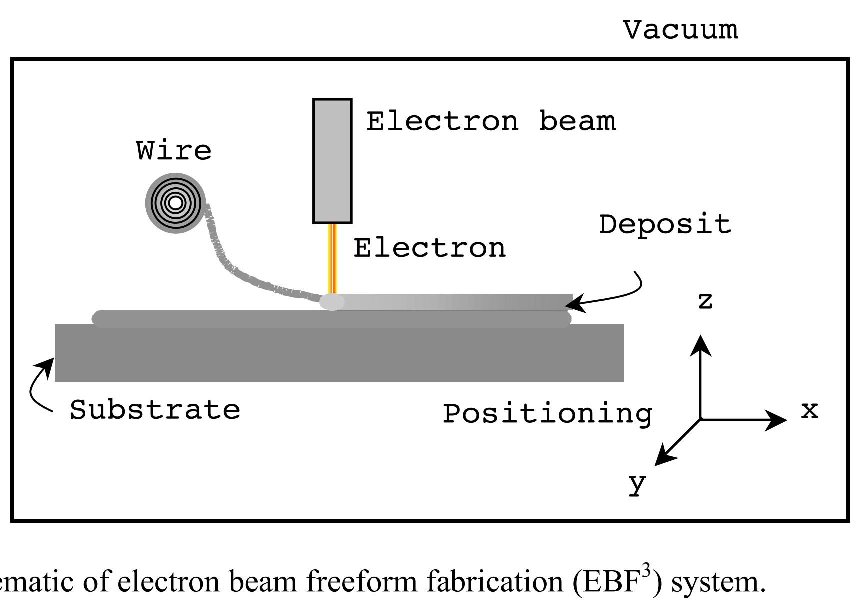

Figure 1. Schematic of electron beam freeform fabrication (EBF^3) system.

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 2500 cm^3 hr^{-1} (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™) process, may be applicable to the EBF^3 process [4 ,5]. The LENS™ 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 LENSTM 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 direct variables than that of the LENS™ process, which permits development of a different closed loop control methodology and ability to achieve finer process control.

Control Methods

The EBF^3 process has four input parameters that affect five output parameters. The input parameters are beam power, beam pattern, travel speed, and wire feed rate. Variations in these parameters influence the weld's height and width (or geometry), the metal composition (or chemistry), residual stresses within the final part, and distortions of the final part. The input parameter interactions are complex and non-linear and currently require trial and error, and expert human experience, to find desirable combinations. Even when a set of good parameters is found, that is, input parameters that yield a good 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 EBeam process control: feed forward, course 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 applications, design challenges for those applications are also discussed.

Feed Forward (or open-loop)

The term "feed forward" is used to indicate that information about the welding 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 reduces the part definition to layers that will be built in the additive process. Third, EBeam control parameters are manually inserted into the file of tool path commands. Fourth, CNC (Computer Numeric Control), EBeam control parameters and tool path commands, are given to the welder to produce the part.

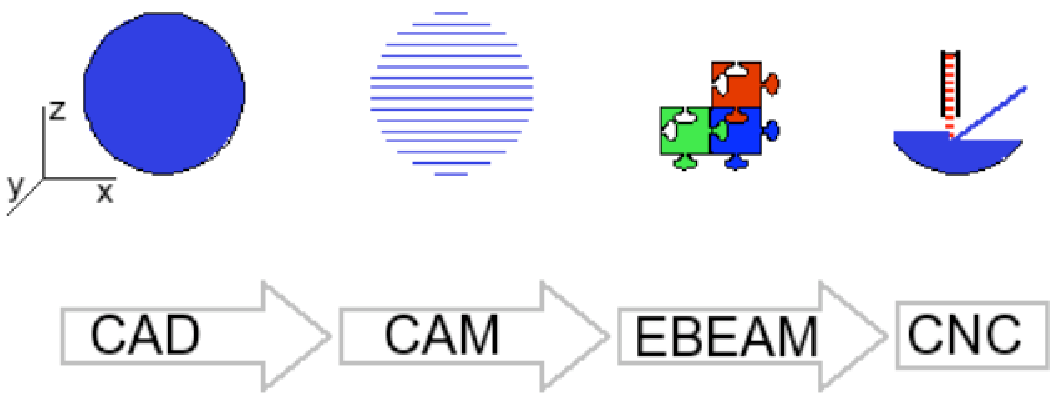

Figure 2. The classic approach used for subtractive manufacturing with an additional step, EBEAM, needed for EBF3 additive manufacturing. The arrows represent a step-by-step process with information flow only in the forward direction.

The non-linear relationships between input parameters and their role in a welds final chemistry was show in a recent DOE (Design Of Experiments). Figure 3 shows travel speed and beam power each taken individually play a very small role in weld chemistry. Collectively they play the second strongest role in characterizing the weld chemistry while not adding together in a linear fashion.

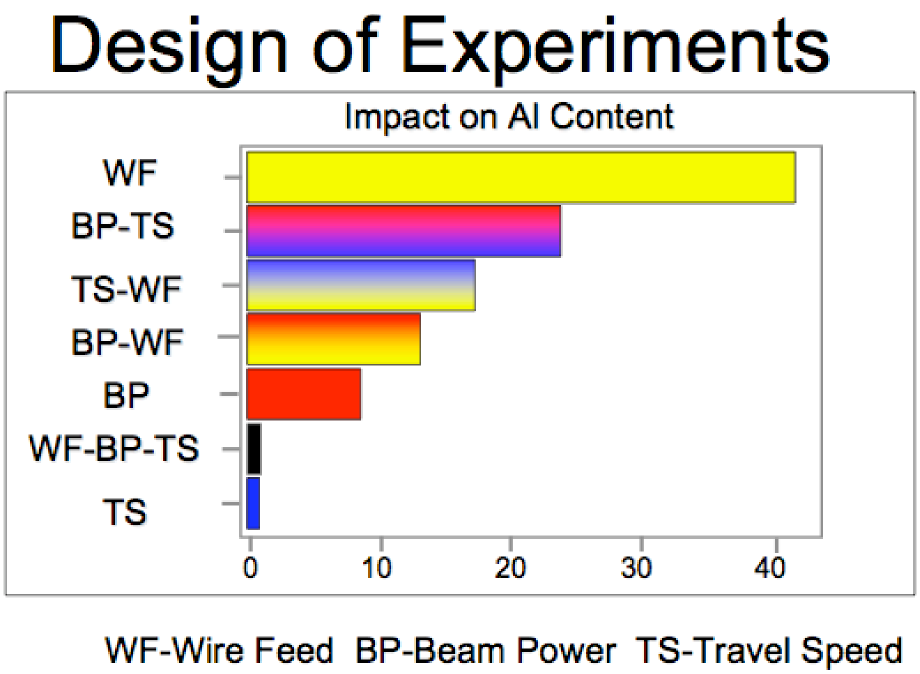

Figure 3. Design of Experiments results showing the complex interaction of wire speed, beam power, and travel speed and their impact on Aluminum chemistry

The main advantage of a feed forward process control is its apparent simplicity since the EBeam 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 EBeam 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 beam power and wire feed 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, sometimes without success.

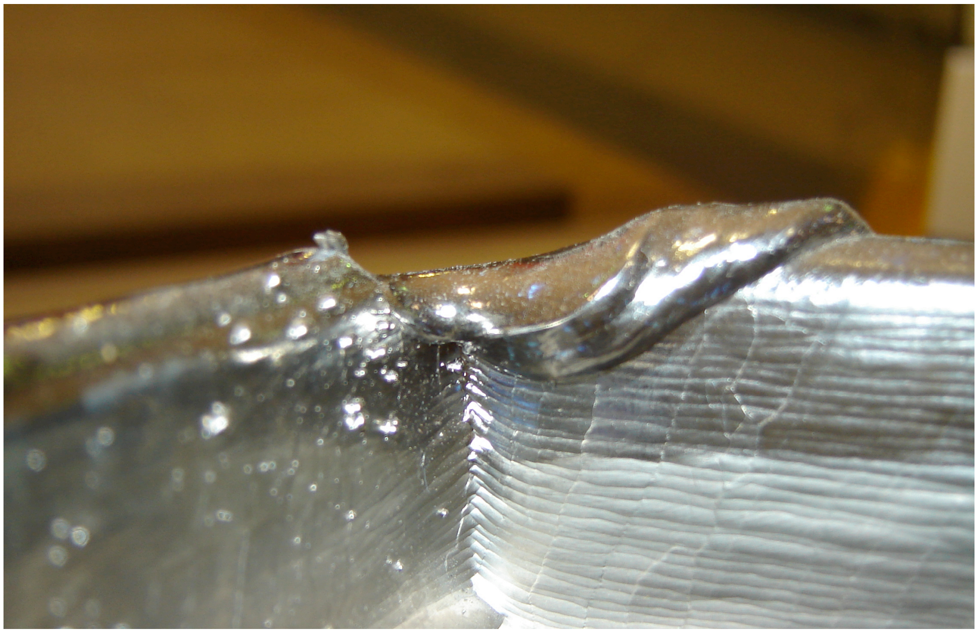

Figure 4. A build error after about 50 successful layers. A small error in one layer becomes larger in subsequent layers.

The feed forward method can be improved through extensive DOE and other research. 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. It must be stated that these relationships need to be understood for the feed forward method, and for any other type of control method. It may be possible to accomplish relatively simple builds without feedback, but experience is showing that some level of feedback control will be necessary for more complex builds.

Course feedback

Here we introduce course feedback control. This method closes the 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). Ebeam process parameter information is 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 weld is taken. That height information feeds back into the system and is used to compute what layer height will be taken next from the CAD description. For instance, if a weld height of 0.030" was assumed but an average weld height of 0.025" was measured, the next layer from the CAD drawing will be taken from 0.025" above the previous layer. This 0.005" error, if propagated over 100 layers, results in a part that is 0.5" too small and features along the height of the build will be lower than anticipated. If the part will need final machining, the CNC machining commands, which assume a good build, will not yield a satisfactory part.

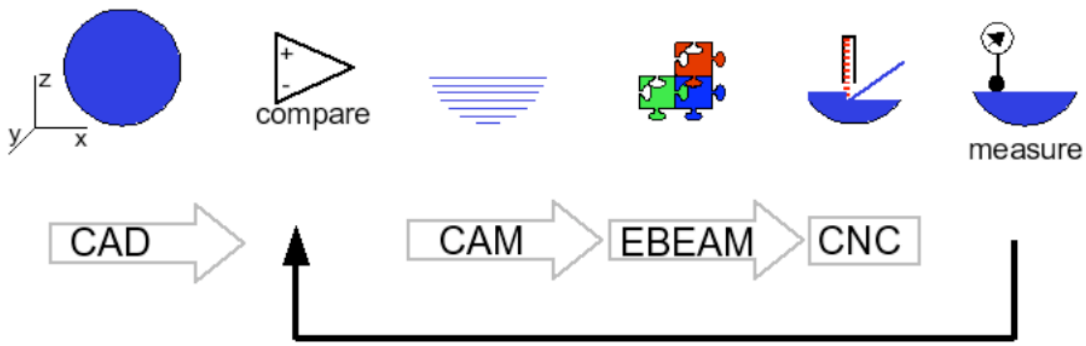

Figure 5. Adding a feedback path to the feed forward approach. Here the direction arrows show a feedback path of information that will be used to plan the next layer of the build.

Corrections are not limited to layer height. If an error occurs and a depression is measured along the tool path, the EBeam step can modify the EBeam parameters for the next layer so 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 EBeam 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 EBeam process.

The main advantage of course 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 are relatively simple and may be available off-the-shelf from the welder manufacturer. Once geometry information is obtained, comparing that information with the CAD diagram is a relatively simple process. Any equipment used to monitor the build must work in a vacuum and deal with metal vapor deposition. Since measuring can be accomplished while the EBeam is off, shutters can protect the device from metal vapor deposition.

An additional benefit to a relatively simple system is desirable for space based applications. First, additional equipment adds weight and directly influences launch costs. Secondly, even before launch, a simpler system is easier to integrate and test. Thirdly, a more 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 welding process in real-time. Figure 6 shows the flow of information for this method. As with the feed forward and course 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 EBeam 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 EBeam welder is building a layer, the process is closely monitored and information is immediately available for feedback. The weld information stream is compared with the desired commands and an error signal is used to tweak the CNC controller.

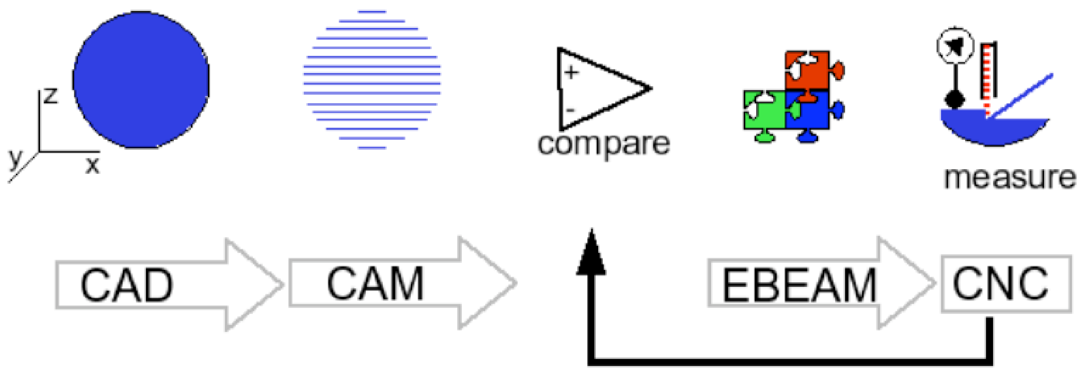

Figure 6. Adding a fine loop feedback path. Here the direction arrows show a feedback path of information that will be used to correct the CNC controls in real-time. In comparison to the coarse feedback control the CAM information, or the layers of the build, are all computed once.

Melt pool temperature, melt pool geometry, and the height of the build are the likely parameters for monitoring the welding 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 weld process from layer to layer (for geometry and chemistry).

Temperature and melt pool geometry appear to be interrelated and monitoring temperature alone may be enough for 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 bride 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 the circuit that controls the welders Z height.

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

The advantage of this 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 increases quality and reduces the need for operator intervention. 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, potential increases maintenance requirements, and potential reduces reliability.

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, distortion. 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 EBeam parameters are issued to add missing material. Selection of successful EBeam parameters is dependant 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.

Conclusion

This paper summarizes the current state of knowledge related to closing the control loop on the EBF^3 process. Terrestrial and space based challenges have been addressed in regards to adding sensors to monitor the weld process. Some of the challenges are technical, other are related to readying a new system for space flight.

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