ADVANCED ELECTRON BEAM FREE FORM FABRICATION METHODS & TECHNOLOGY

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Abstract

Electron Beam Additive Manufacturing (EBAM) and Electron Beam Free Form Fabrication (EBFFF) are processes that utilize proven EB Welding technology to create metallic parts using a cost effective approach. Using today's CAD modeling capabilities, EBAM / EBFFF deposits feedstock material in an additive layering process to produce near-net-shape preforms. These processes are ideally suited to a wide range of aerospace materials including many reactive and refractory alloys.

A process description in addition to the latest advances in the EBFFF equipment design will be presented. Examples of parts built with this process will be presented with cost and lead-time comparisons to conventional manufacturing methods. This paper will focus on additive manufacturing of aerospace structural components using the EBFFF technique. This process most closely resembles laser additive manufacturing which has been in development for a number of years by several commercial and academic organizations. The electron beam (EB) process offers unique advantages over other currently available processes in terms of power efficiency and deposition rate.

Introduction

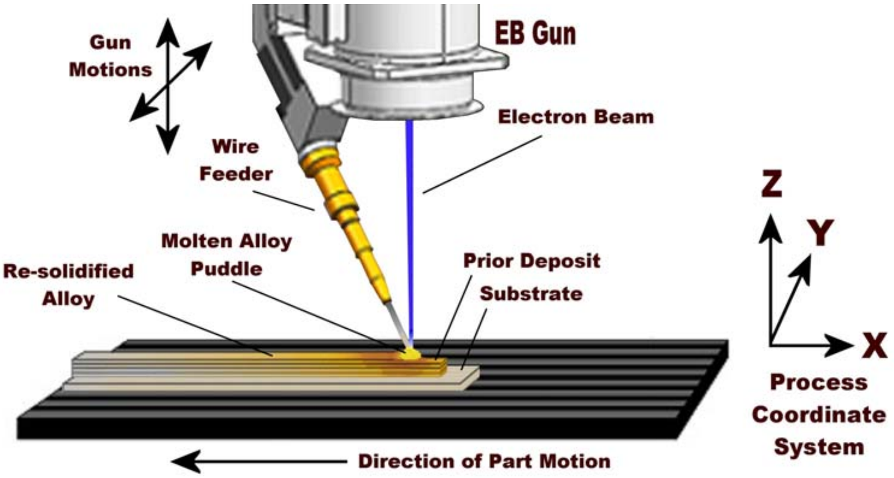
Over the past decade, many solid freeform fabrication techniques have been investigated to create fully dense metal parts using a variety of heat sources[i]. Numerous groups have attempted to fabricate components in a way that material efficiency and lead-time are improved, targeting reductions in the cost of fabrication and lead-time compared to conventional methods. The basic concept behind all additive manufacturing is to take mass-produced raw material, and through the use of an innovative processing technique, generate a finished component minimizing the use of specialized or dedicated tools.

The ability to rapidly procure components for the aerospace industry is severely limited by the lead-time for raw materials, tooling (casting molds and forging dies, etc.), design, and the actual manufacturing of components. EBFFF has the potential to greatly reduce the manufacturing lead-time and cost for components by reducing the volume of materials required along with the resulting machining time, eliminating the need for hard tooling, and improving the flexibility of the design process.

EBFFF makes use of commercially available "welding wire" as its feedstock material. The welding wire is deposited on a substrate plate of like material. Large depth-to-width ratio parts (ribbed aircraft structures, spars, etc) are ideally suited to this processing method. The development of this process is largely being driven by the goals of the companies within the *Metals Affordability Initiative Consortium (MAIC).*[ii]

With the EBFFF fabrication method, metallic preforms can be manufactured from computer-generated 3D drawings or models. In this operation, the deposition path and process parameters are generated from post-processing the virtual 3D model and executed by a real-time computer control. The deposition takes place in a vacuum environment, typically in the range of 1×10^{-4} to 1×10^{-5} Torr. The wire is directed toward the molten pool and melted by a focused EB. Parts are built up layer by layer by moving the EB and wire source across the surface of the underlying material that is commonly referred to as the substrate, as shown in Figure 1. The substrate material can become an integral part of the finished product. In this manner, free-standing shapes, or preforms, are generated without molds or dies. Conventional techniques are then used to machine the preform to the final part geometry.

Figure 1: Schematic Diagram of the EBFFF Process



EB technology is well suited for the EBFFF process due to the electrical efficiency, beam to material coupling, and the many decades of proven CNC process control on stringent aerospace EB welding applications. Also, the vacuum environment typically employed with EB systems provides an optimal environment for reactive alloys. The aerospace industry has been commonly using EB welding systems since the early 1960's.

As a high energy beam, EB is often compared to laser. The EB process has a number of advantages over high power lasers (in this paper, high power lasers are defined as CO_2 laser having a minimum output power of 10 kW). The EB is electronically focusable and the output power is scalable over a very wide range. This allows fine detail (0.030" wall thickness) to be deposited using power output as low as several hundred Watts, while high deposition rates (greater than 40 lbs. per hour) can be achieved with the same system at higher power levels. The EB process is inherently power efficient, on the order of magnitude of 90% or better. The power efficiency of CO_2 laser process is about 10%.

Another key advantage over laser beam processing is the coupling efficiency of the EB with the deposited material. For optical energy such as a laser beam, the reflectance for metals at room temperature can range from 40% to over 95%[iii]. Thus, a portion of the incidence energy is reflected out of the melt pool and lost to the atmosphere. This prohibits some materials such as aluminum from being effectively deposited with a laser. The coupling efficiency of an EB is very high and allows highly reflective materials to be deposited efficiently. Also, because the EB process is typically operated within a high vacuum environment, this provides for an oxygen-free atmosphere. Therefore, secondary inert gases are not required to insure the chemical integrity of the material.

Metallurgical Summary

Microstructure: [iv] The Ti-6Al-4V microstructure of an EBFFF buildup is comprised of extremely large columnar grains growing epitaxially from the substrate, as shown in Figure 2. Figure 3 shows the microstructures of LAM and EBFFF samples, heat-treated to 1675°F for 2-hours and aged at 1000°F for 4-hours with no significant differences in microstructures.

Figure 2: Microstructures of EBFFF Ti-6Al-4V, as deposited

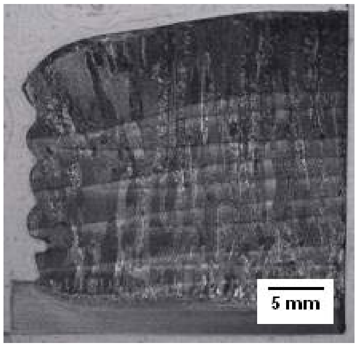
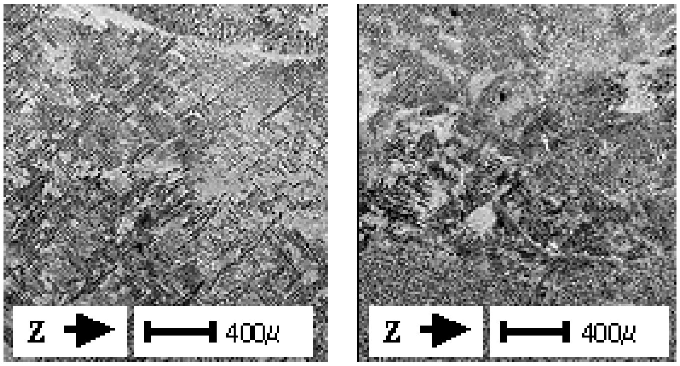
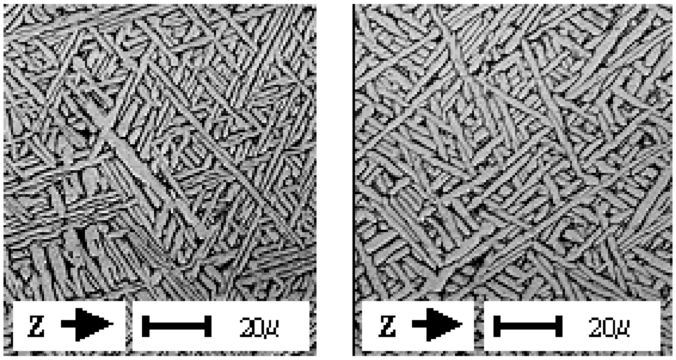


Figure 3: Microstructures of LAM and EBFFF Ti-6Al-4V, Post Heat Treated



LAM – high magnification EBFFF – high magnification



LAM – low magnification EBFFF – low magnification

Mechanical Test Data: [iv] As reported at the AeroMat 2003 Conference, EBFFF deposits were compared to LAM deposits. The findings concluded that the Tensile, Fatigue Crack Growth, and Strain-Life Fatigue properties for both processes were all comparable, as shown in Table 1, Figure 4, and Figure 5.

Table 1: Tensile properties comparison between LAM and EBFFF

Orient	**Deposit Process**	**Strength (ksi)**		**E (Msi)**	**Elongation (%)**	
		UTS	**0.2% YS**		**TOTAL**	**R. A.**
Z	EBFFF	134	123	16.9	13	35
	LAM	137	122	16.8	15	37

Figure 4: Fatigue Crack Growth

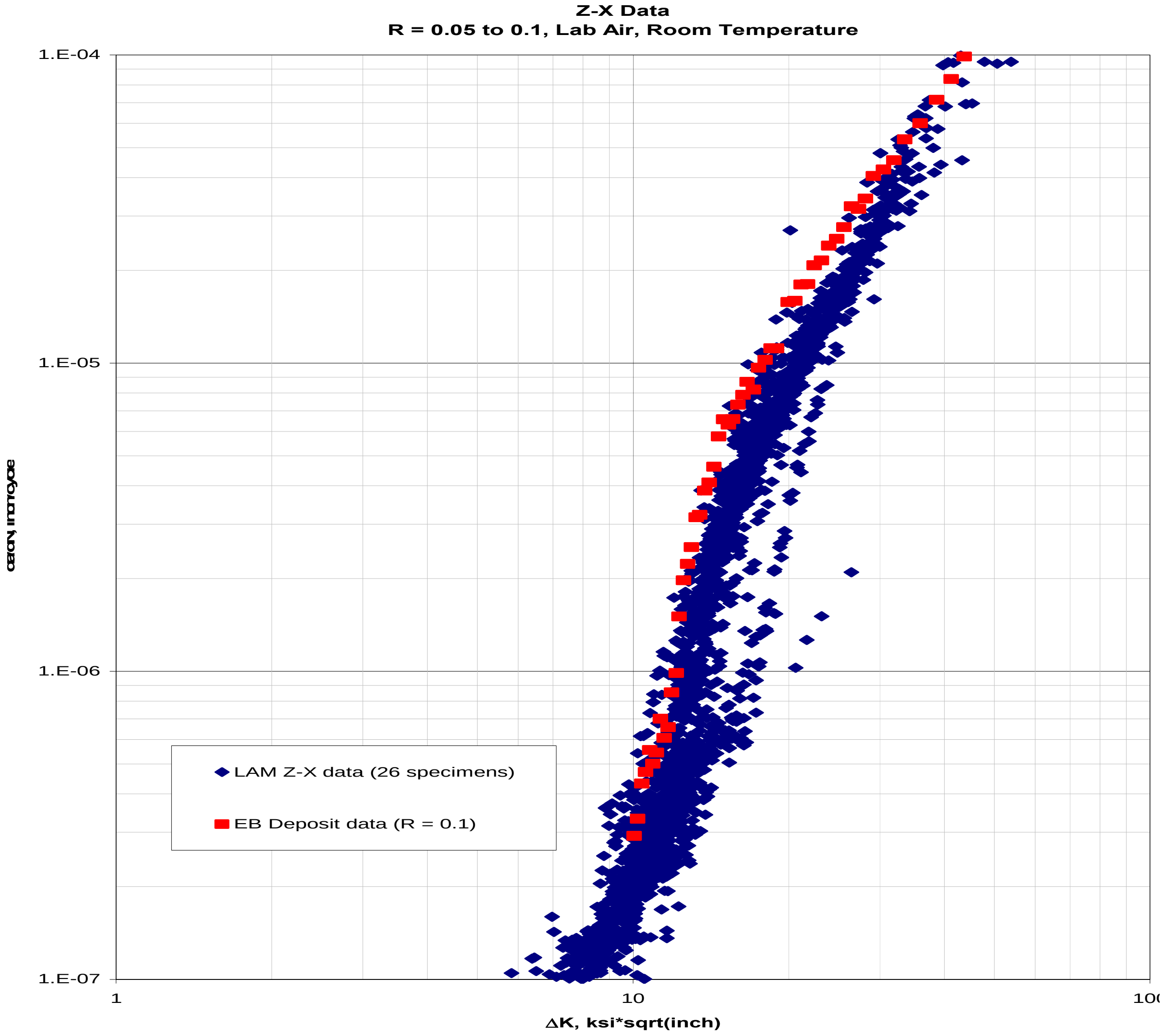
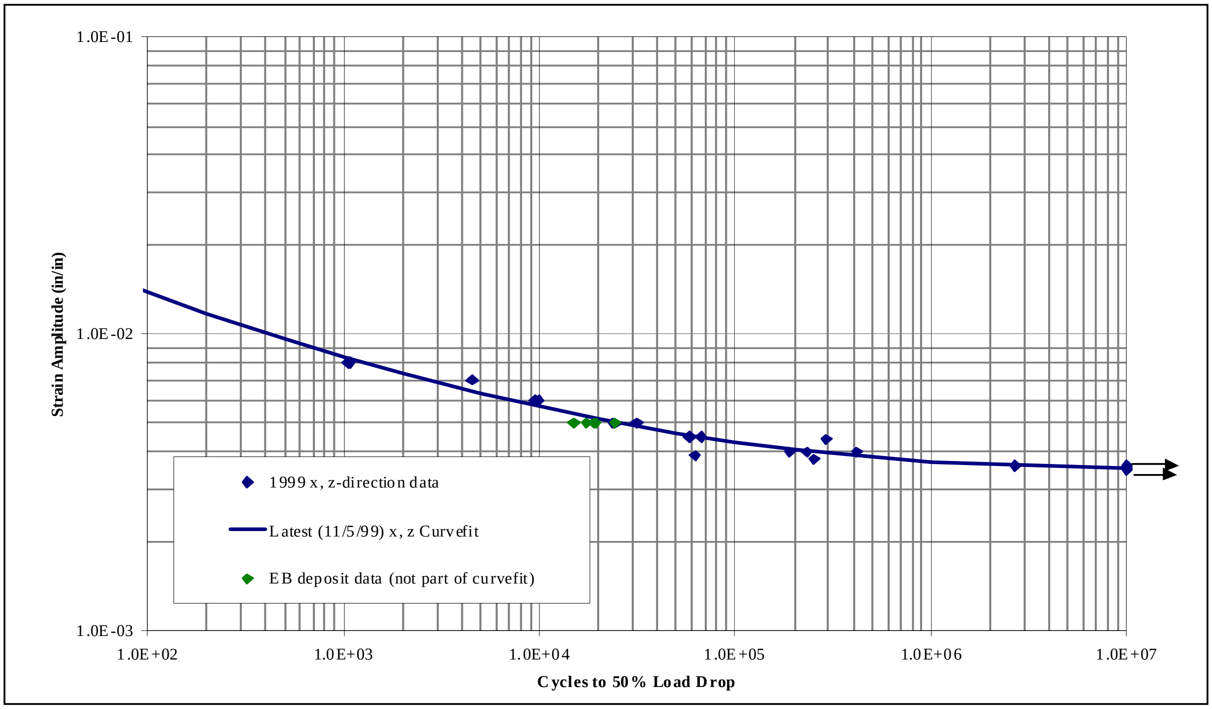


Figure 5: Fatigue Strain vs. Life Fatigue, R = -1, ε_{max} = 0.005



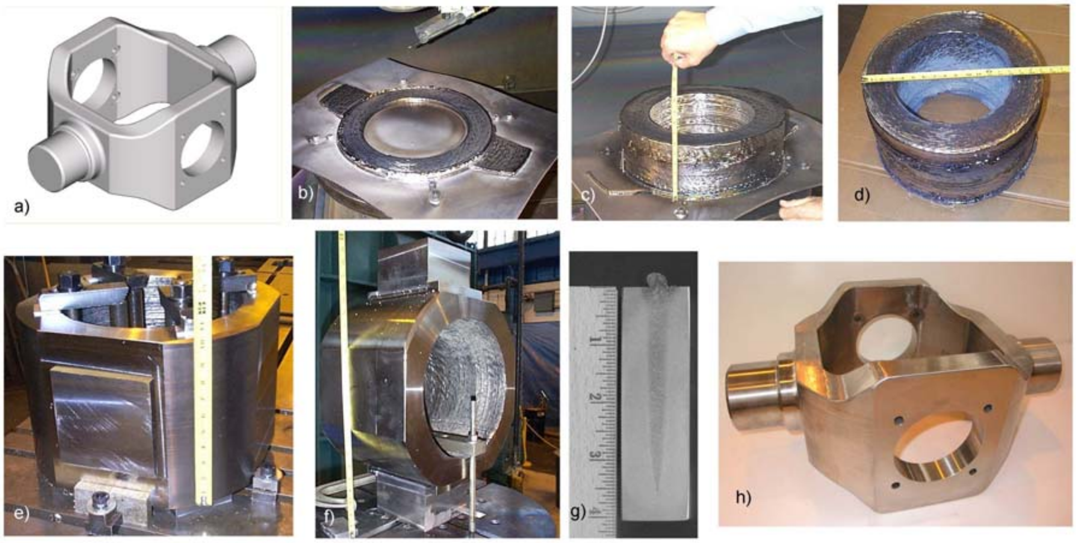
Case Studies

The following are examples of two EBFFF case studies that were explored to develop process techniques, feasibility, and proof of concept when compared to conventional manufacturing methods. In each example, the part integrity and economic models were analyzed to determine the viability of the process.

Gimbal: This part was selected primarily because of its finished part size relative to the high volume of material that would need to be removed (through conventional machining methods) to produce the component. Furthermore, this project verified the ability to overcome long lead-times by producing a replacement part that was not available from the original equipment manufacturer (OEM). Figure 6 shows a progression of images that outline the build process from model to finished product of a “gimbal” assembly. The main body of the gimbal was deposited using EBFFF and the trunnions were cut from off-the-shelf stock material and conventionally EB welded to the body. This dual process capability is one of the unique features that existing EBW technology offers, and allows the user to take advantage of the most cost-effective approach to building a part. One EBW system is equally capable of the fabrication of new parts using the wirefeed system, as well as producing the typical high depth to width ratio weld profiles that the EBW process has been performing for decades.

Figure 6. Gimbal Assembly Illustration & Photos

a) solid model b) initial base layers c) deposit at halfway point d) final deposit layers e) initial assembly with machined pads, preparation for EBW f) assembly with EB welded trunnion blocks g) EB weld cross section h) finished product



The work was performed using a Sciaky low voltage EB welder with a standard 60/60 model (60 kW / 60 kV) gun arrangement along with a wirefeed assembly. For this project, 0.093” Ti-6Al-4V wire was used and the wirefeed rate was set at 70 IPM (1780 mm/min). Based on previous experience, weld parameters were chosen to include a power setting of 40 kV at 70 mA (2800 W), and a surface travel speed of 20 IPM (510 mm/min). Additional parameters included a gun-to-work distance (GTWD) of 9 inches (230 mm), and beam oscillation to provide circular motion at 1000 Hz. The buildup was performed on a titanium plate that was ¼ inch (6.4 mm) thick by 24 inches (610 mm) wide by 30 inches (760 mm) long. This plate was chemically cleaned and was clamped to the faceplate of the rotary table via four mounting bolts. The process ran with a deposition rate of about 5 lbs/hr (2.3kg/hr)[iv].

The approximate final dimension of the cylinder before machining was 11 inches (279 mm) high with an outside diameter of about 17 inches (432 mm), and a 3 inch (76 mm) wall thickness resulting in an as deposited mass of approximately 220 pounds (100 kg). If the assembly was machined from a solid block billet, this represents a reduction of over 50% in material savings when compared to conventional hogout machining.

Chord: Sciaky produced a structural “Chord” for a major aerospace company. This part was selected for similar reasons as the “gimbal” because of the high cost and lead times associated with obtaining Ti-6Al-4V, as well as the large mass of material that is needed to be removed to produce the finished part.

The CAD model was used to generate a CNC weld path offline, as shown in Figure 7. It was determined that a minimum of .200” excess material would be deposited such that a final net shape part could be machined from the preform. A 6” x 60” x 0.5” Ti-6Al-4V substrate plate was clamped to a work platen and processed using Sciaky’s EB VX300 system. This system was equipped with CNC XYZ axes, wirefeeder, and our standard 60/60 low voltage EB welding gun. The system is capable of providing up 42 kilowatts of power. The preform was deposited at a rate of over 7 pounds per hour. The parameters selected resulted in a single pass buildup with approximate dimensions of 0.62” wide by 0.12” high. The preform shape was built to a height of 3.5 inches tall. After thermally processing the preform, it was machined to net size. Figure 8 depicts the Chord in process and its final finished form.

Figure 7: CAD Model of Target Preform

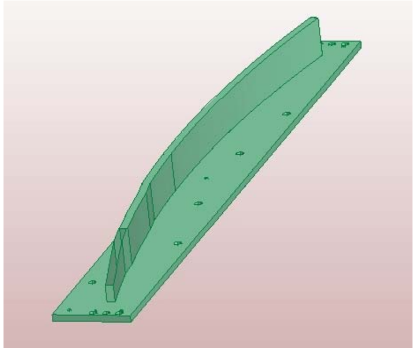
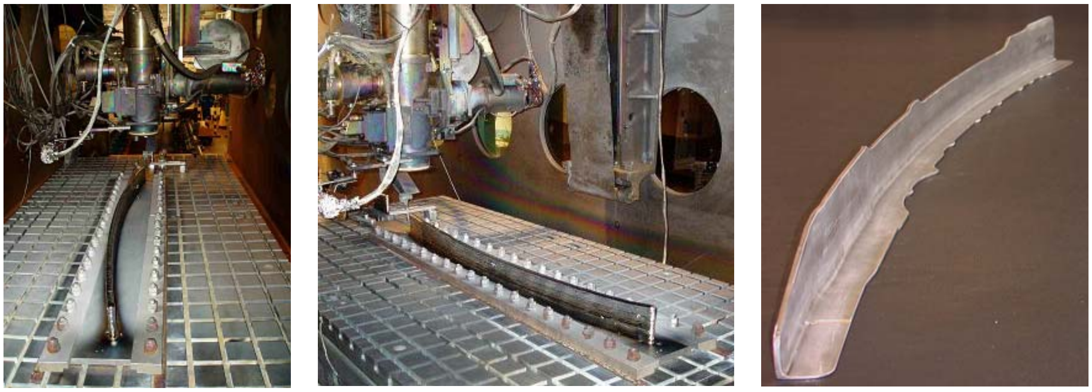


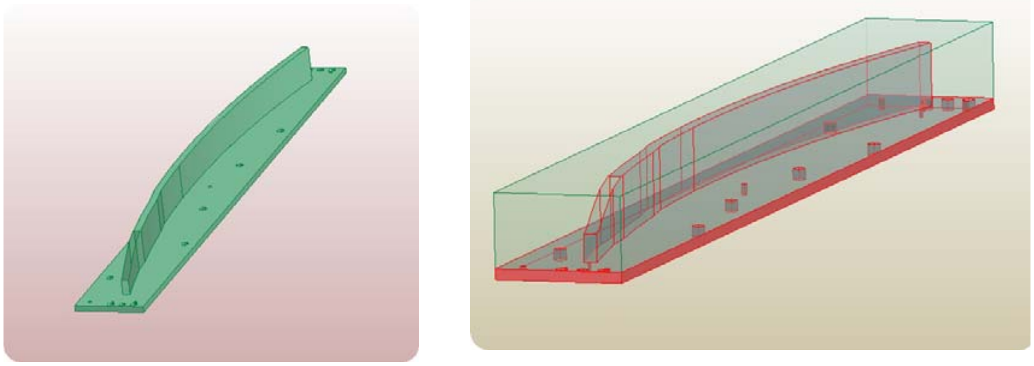
Figure 8: Deposited Chord Preform and final part



Cost Analysis

A comparison of material volume is shown in Figure 9. The time required to machine the chord from the above mentioned “hogout” versus the final machining for completing the chord is presented in Table 2. The estimates assume the use of typical machining parameters for Titanium 6Al-4V material[v]. It should be noted that this estimate has been generated for comparison purposes, and should not necessarily be construed as the only way to generate the subject part. Even with this disclaimer, it is easy to extrapolate that in order to start with close to 80% more raw material with a hogout versus EBFFF deposit that the machining time will be proportionally larger as well.

Figure 9: Comparison of material volume - EBFFF buildup vs. hogout



EBFFF Material Usage
Substrate Plate – 60”x6”x0.5” = 29 lbs
Deposit – 57”x0.65”x3.5” = 21 lbs
Total Material = 50 lbs

Estimated Hogout Material
Bar Stock – 57”x6”x4” = 218 lbs

Final Machined Part Weight = **4.5 lbs**
EBFFF material usage efficiency is approximately **79%** better than hogout.

The cost of using the EBFFF process depends on a couple of interrelated variables. These cost elements are associated with market pricing of raw materials and deposition rate. The cost of raw materials is independent of the process and driven by industry demand and availability. Deposition rates for titanium have been demonstrated up to 40 lbs per hour. It should be noted that techniques to allow for higher deposition rates are continually being refined. Based on current experience and power availability with EB welding systems, deposition rates approaching 50 pounds per hour can be achieved.

In order to complete the cost justification of this case study the total effort to generate the EBFFF preform must be included with the final machining costs. Table 3 compiles the total comparative cost relative to each specific approach. Other costs such as CNC programming and project management would likely be equivalent for either process, and are therefore not included in the presented data.

Table 2: Machining Estimates

Machining Costs - Hogout		
Assumptions		
Cutter Type	HSS	
Cutter Dia.	1	in
Flutes	4	
cut per tooth	0.003	in
Radial cut	0.667	in
Axial Cut	0.125	in
Lateral Passes	9	
Axial Passes	21	
SFM	60	ft/min
Feedrate	2.75	in/min
Time Per Pass	20.73	min
Total Passes	189	
Total Machining Time	3917	min
	65.3	hrs
Rate	$ 100.00	per hr
Cost	$ 6,528.62	

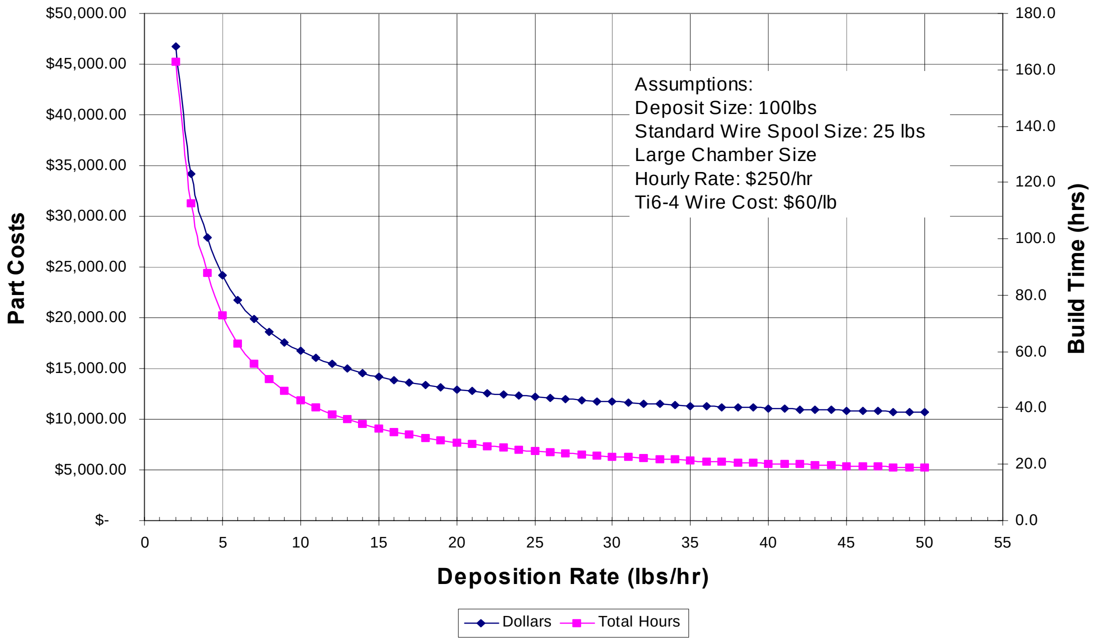
Finishing Machining Costs - EBFFF		
Assumptions		
Cutter Type	HSS	
Cutter Dia.	1	in
Flutes	4	
cut per tooth	0.003	in
Radial cut	0.667	in
Axial Cut	0.125	in
Lateral Passes	9	
Axial Passes	4	
SFM	60	ft/min
Feedrate	2.75	in/min
Time Per Pass	21.82	min
Total Passes	36	
Total Machining Time	785	min
	13.1	hrs
Rate	$ 100.00	per hr
Cost	$ 1,309.00	

Table 3: Total Cost Comparison Case Study – Chord

Cost Summary	
EBFFF	***Hogouts/Machining***
Raw Material (substrate plate) - $1,500	Raw Material - $10,900
EBFFF Deposition (assumes 15lbs/hr, cost of wire) - $4,500	
Aux. Processes (Thermal Processing) - $2,500	Finish Machining - $6,530
Finish Machining - $1,310	
Total: $9,810	**Total: $17,430**

Figure 10: Cost as a Function of Deposition Rate

Cost based on Standard EB Weld Technology as of 2-23-06



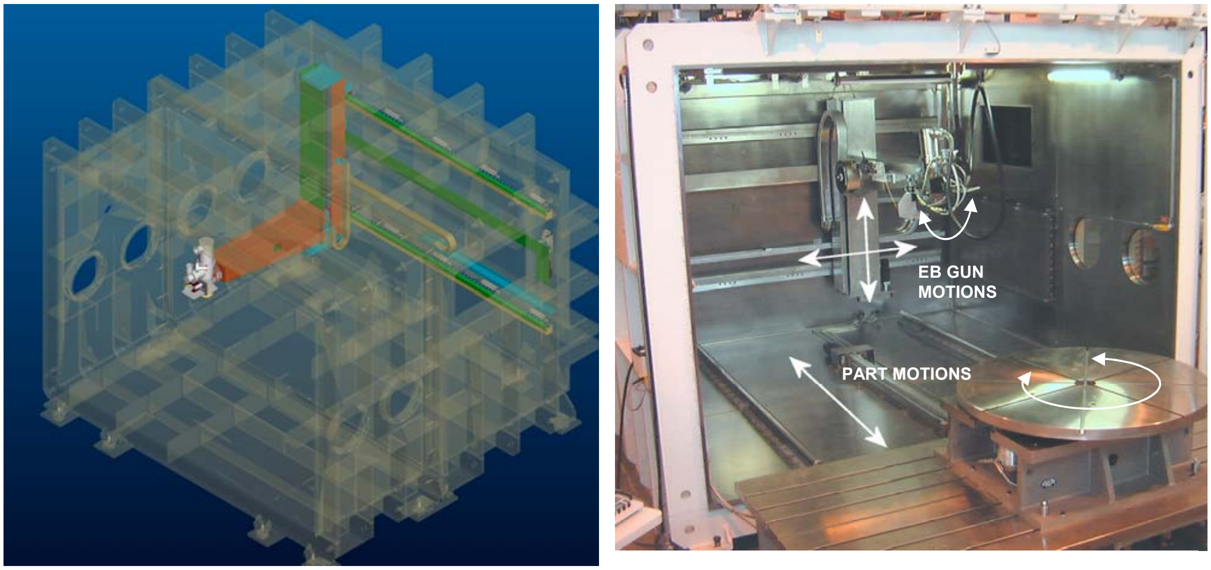
Equipment Advances for EBFFF

With the advent of the EBFFF process, Sciaky has introduced a new generation EB System. This system has been specifically engineered for applications using both EBW and EBFFF processing, as shown in Figure 11.

The new designs have optimized the reliability and performance of the mechanical motions, wirefeed assembly, power supply and vacuum system. The mechanical motions are designed in either robust boom or gantry configurations to maximize the work envelope, as shown in Figures 12 and 13.

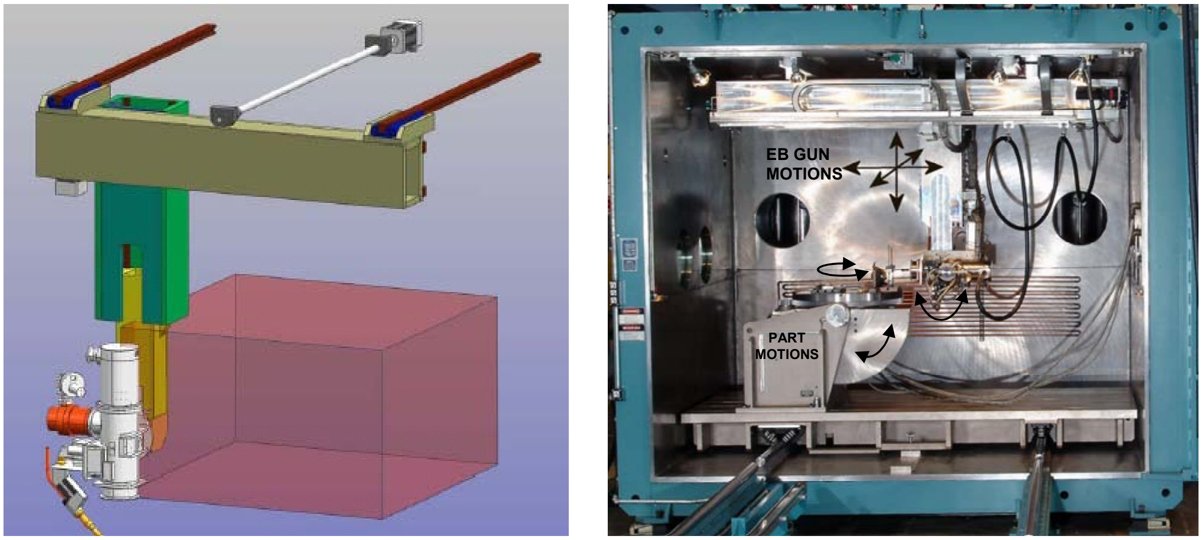
Figure 11: Sciaky's New Generation EBFFF System

Figure 12: Sciaky's Boom Style Configuration



(a) Boom Manipulator CAD Model (b) Boom Manipulator Actual System

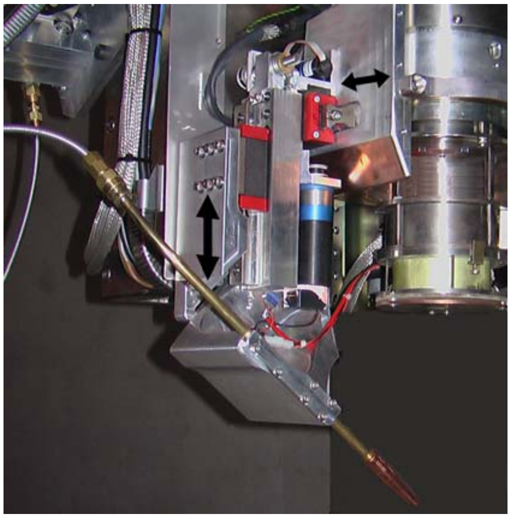
Figure 13: Sciaky's Gantry Style Configuration



(a) Gantry Manipulator CAD Model (b) Gantry Actual System

Mechanical Motion & Wirefeed System: To meet the demands of the EBFFF process, the motion control is designed to handle the added load of the heavy-duty wirefeed system. This wirefeed system has been engineered to meet the high deposition rates associated with the process and includes a wire straightener with a rugged drive and wire guide arrangement, as shown in Figure 14. In addition to the motion control and wirefeed system, an in-process distortion feedback system and a high-speed beam rastering arrangement can be employed to further increase deposition rates and reduce overall processing time.

Figure 14: Sciaky's Remote Operated Wire Positioner



Conclusion

The EBFFF process has shown to be a leading candidate for generating large near-net-shaped performs. It has been demonstrated that significant cost savings can be realized using this process when compared to conventional processes due to the reduction in raw material usage and minimized lead times. The current state of the art EB systems are being developed to meet the immediate demand presented by the aerospace industry. While this paper focuses on Titanium alloys within the aerospace industry, EBFFF is suitable for fabricating a wide range of structures using a number of engineering alloys.

References

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[v] SupraAlloys Web Article - http://www.supraalloys.com/Machining_titanium.htm (1 of 14)1/22/2006 4:55:02 PM