Laser Heated Electron Beam Gun Optimization to Improve Additive Manufacturing

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Abstract

Electron Beam Additive Manufacturing requires to improve electron gun characteristics to become a highly competitive manufacturing process. Our work targets the optimization of beam focusing to reduce the beam spot size, to improve the beam deflection system resulting in higher positioning accuracy, to refine thermal stability by minimizing heat induced drifting and to introduce a new powder delivery device which can be synchronized to beam parameters. Heisenberg's uncertainty principle states that if a position of a particle is precisely known, its momentum becomes less accurate and vice versa. Therefore, it will be required to conceive gun parameters optimizing the balance of opposing laws. Our goal is to deliver an open platform electron beam additive manufacturing machine which utilizes the results presented in this paper.

Introduction

Figure 1 shows super conducting high temperature materials such as niobium and its alloys supported by an aluminium or copper lower structure. These materials present complex metallurgical and dimensional problems. With varying melting temperatures and thermal conductivities, the beam optimization for additive manufacturing of radio frequency (RF) structures becomes challenging. Our optimization work includes improving many of the control loops used in the deflection control system and changing the beam characteristics.

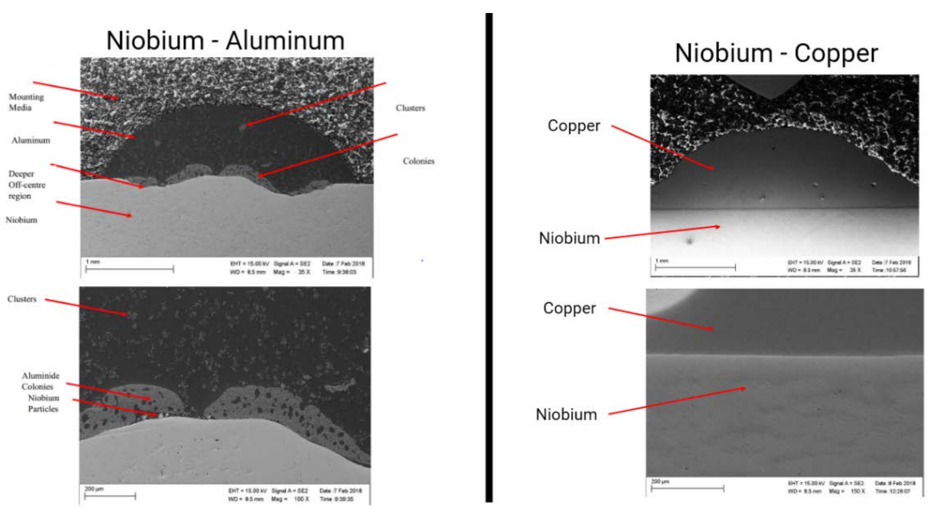


Figure 1 Niobium material cross section from initial melt experiments

Discussion

Laser Heated Electron Beam Gun

The optimization work discussed is based on our patented laser heated electron beam gun shown in Figure 2. The gun allows the use of standard or custom cathodes which is enabled by using a laser diode with 808 nm wavelength focused directly onto the cathode. The laser optics are fully electrically isolated from any of the high voltage and, thus, allow fast switching variable energies or modulation of the acceleration voltage between layers.

The electron beam current is controlled by a bias system that can be operated in continues or pulsed mode. Below the cathode is an anode with space for alignment coil and/or stigmatic correction systems.

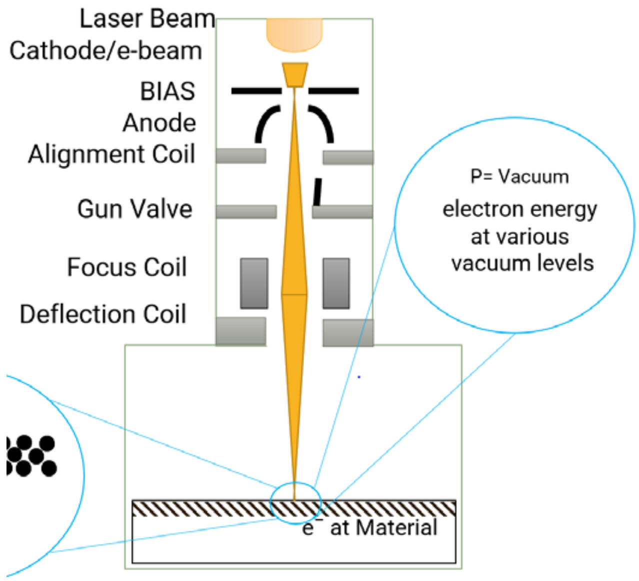


Figure 2 Schematic of laser heat electron beam gun

A separation valve isolates the upper beam column from the process chamber. Below the gun valve, the lower beam column holds the focusing and deflection coils and can have an optional optical vision system to view the melt pool from above. These coils control the beam position and the beam spot size. Improving the electron beam additive manufacturing process includes working on focusing techniques that can deliver spot sizes of 10 µm to 50 µm.

Beam spot sizes are a not only depended on the electron optics, other process parameters such as the vacuum level in Figure 3 (Meleka, 1971) impact the electron trajectories as well. The vacuum levels in the gun most commonly depend on chamber pressure and strength of the differential pumping capabilities of the gun vacuum pumps. The differential pumping assumes that the gun valve is open and, therefore, the typical gun pressure ranges from E-3 to E-5 Pa (or E-5 to E-7 mbar/Torr). The vacuum of the chamber (Macro Pressure) depends on the chamber pumps and processing conditions during material melting. Typical vacuum in the chamber ranges from E-1 to E-5 Pa (or E-3 to E-7mbar/Torr). In addition to the pressure in the chamber, melting with small spot sizes may create strong vapour pressures (Micro Pressure), localized at the melt pool. These vapours, combined with outgassing during the melting, may move powder particles.

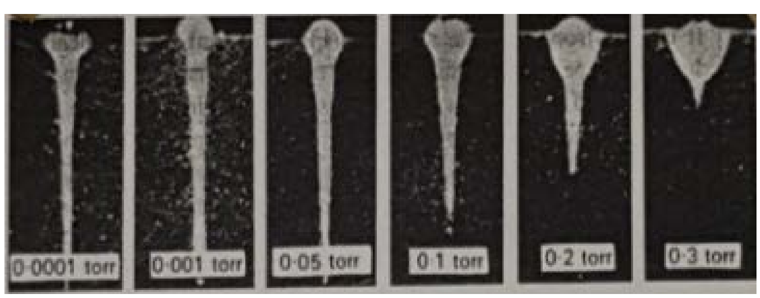


Figure 3 Electron beam melting as function of vacuum pressure

Electron Beam Cathodes

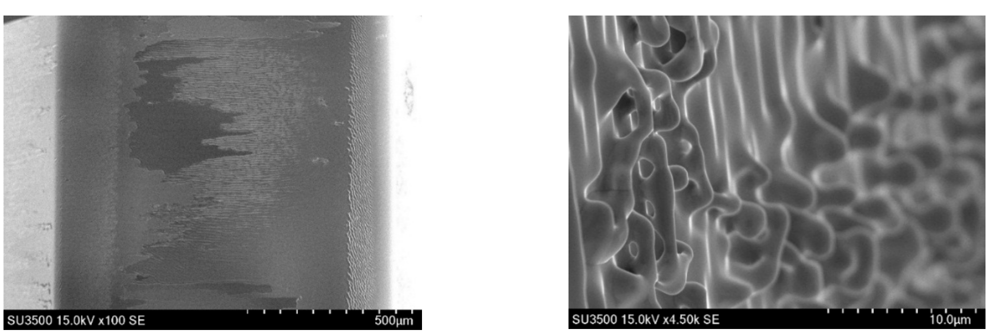
The vacuum level in the gun has a direct impact on the performance of the cathodes used in an electron beam gun. Electron Beam Additive Manufacturing uses mostly two cathode (filament) materials, namely Tungsten and LaB_6. Both materials have very specific characteristics as listed in Table 1, and impact the mode of operation in the electron beam gun. In addition to the 2 existing materials, carbon nanotube cathodes show excellent electron emission properties for high brightness beams. Due to the lack of experimental data and availability of existing cathodes it is not clear if this cathode material can be used.

	LaB_6	**Tungsten Filament**	**Future: Carbon Nanotube**
Working Temperature (K)	1500	2700	Direct photon - electron emission
Brightness at working temperature (A/cm^2)	1	1	~100 times
Maximum Temperature (K)	2000	--	To be determined
Maximum Brightness at high temperature (A/cm^2)	100	--	To be determined
Operating vacuum (Pa)	e-5	e-3	To be determined
Typical service life at operating pressure (hr)	1000+	30-200	To be determined

Table 1 Experimental comparison of cathode material

Our experiments use tungsten cathodes since sufficient low vacuum pressures cannot be guaranteed during melting as required for LaB6 cathodes. Many LaB6 cathode vendors recommend pressures to be in the E-8 mbar range. This pressure depends on the electron gun design and the vacuum pump sizes.

The structures shown in Figure 1 were produced using tungsten (W) cathodes. Several phenomena were observed during this process. First, using cathodes at higher beam power produces surface coatings caused by back streaming of process material onto the emission surface. This results in vapour from the melt pool coating the surface of the cathode and thereby changing its emission characteristics. In addition, higher cathode temperatures change the new tungsten microstructure from fine grain microstructures to large grain microstructures during heating thereby reducing the electron emission, see Figure 3a. Finally, higher temperatures have shown a physical change of the cathode surface (droplet formation) as seen in Figure 3b. Changes of the cathode surface will impact beam focusing and beam current distribution, which directly impacts the formation of the melt pool.



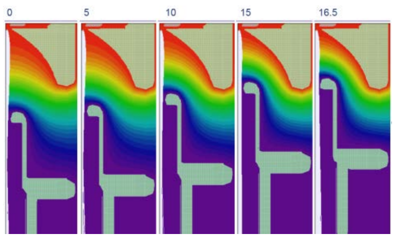
a) Various surface changes observed on used cathode; may result from overheating

b) "Droplet" type surface solidification on cathode caused possibly by overheating

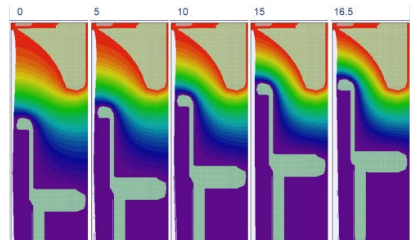
Figure 4 Surface images of used cathodes

Electron Beam Simulation

To better understand the electron gun characteristics, a series of particle trace simulations have been completed. The purpose of the simulations was to establish the most sensitive parameter in the electron beam generation. Various electron gun dimensions were used; we observed that the anode design has a direct strong correlation on the electron trajectory and, as such, the beam focusing. The distance anode to cathode and the shape of the anode drives the energy gradient from high voltage to ground, as shown in Figure 4. Therefore, it directly impacts the electron velocity and maximum current, as shown in Figure 5.



Electron energy gradient for 60kV



Electron energy gradient for 100kV

Figure 5 Electron trace simualtions showing anode sensitivity

By decreasing the cathode-anode distance, the bias (Wehnelt) voltage must be increased to block electron emission. As such, beam current, cathode temperature and spot size can be optimized for various process parameters and beam size and density can be modified. For example, for contour melting smaller spot sizes can be used, whereas for hatching patterns a defocused higher beam current can be applied to increase the melt volume.

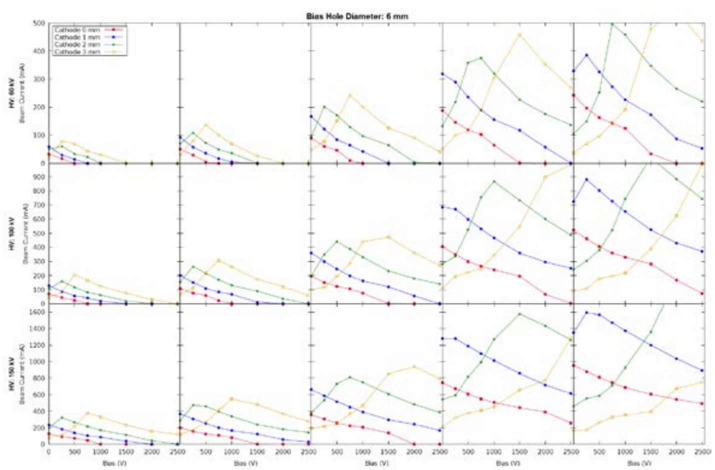


Figure 6 Beam current for various anode settings

It is required to control the temperature of the electron beam gun, as shown in Figure 6, to maintain the electron beam characteristics. Figure 4 shows that overheating the cathode can cause a degradation of the electron emission surface which changes the beam. Various beam parameters are affected by this temperature drift and, therefore, the Upper and the Lower beam column must be temperature controlled. The main devices in the upper beam column are the cathode and anode assemblies. The lower beam column houses the focusing and defection coils. All assemblies are sensitive to temperature drift.

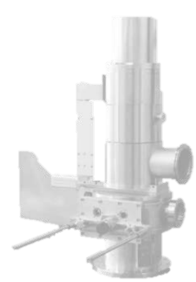


Figure 7 100 kV CANMORA electron gun

Powder Feeder and Dispenser

Fluidization is a widely used process in various industries to achieve continuous powder flowability in a controllable manner. The most common way for powder fluidization is gas fluidization, where solid powder particles are transformed into a fluid-like state through suspension in gas. However, in applications such as Electron Beam Additive Manufacturing, particle fluidization without the usage of gas as a vacuum is required. Our research has shown that powder particles can be suspended by applying a mechanical oscillation which can be tuned to the powder characteristics and dynamically tuned to the process requirements. We developed a powder feeding device (patents pending) based on the frequency modulation, which can be used for powder bed applications as well as for direct melting of powder without preheating.

The device can be built in several configurations according to the process requirements for any number of powder materials and sizes.

Feeding profile	Hole Type	Narrow Slot Type	Wide slot type	Combination
Tanks	1	1	1	1 to 7
Nozzle Sizes	0.5 to 6 mm	Width 10 to 80 mm	Width 80 to 1000 mm	Minimum 0.5 mm hole to 1000 mm slot
Oscillator	1 to 1000 Hz	1 to 1000 Hz	1 to 1000 Hz	1 to 1000 Hz
Controls	Frequency, Amplitude, Level Sensor	Frequency, Amplitude, Level Sensor	Frequency, Amplitude, Level Sensor	Frequency, Amplitude, Level Sensor
Materials	Single Material	Single Material	Single Material	Multi Material with mixing and tank configuration
Process	Direct Melting	Powder Bed	Powder Bed	Powder Bed & Direct Melting

Table 2 Powder feeder configurations

Figure 8 Hole / point feeder

The hole type feeder, shown in Figure 7, can be used for injecting powder directly into the beam and thus, directly melting powder in vacuum. Direct melting can be achieved when the momentum of the powder particles being fed is larger than the repulsive electrical charges created induce by the electron beam in the oxide of the powder.

Figure 8 shows slot type feeders including both, the narrow and wide versions; they are designed to be used in powder bed applications. These devices can be built from any slot size to about 1000 mm width with an unlimited bed length. The feeders will allow for precisely building powder beds to any sizes. It is possible to build feeders larger than 1000mm, although further characterization work is required.

Figure 9 Slot type feeder

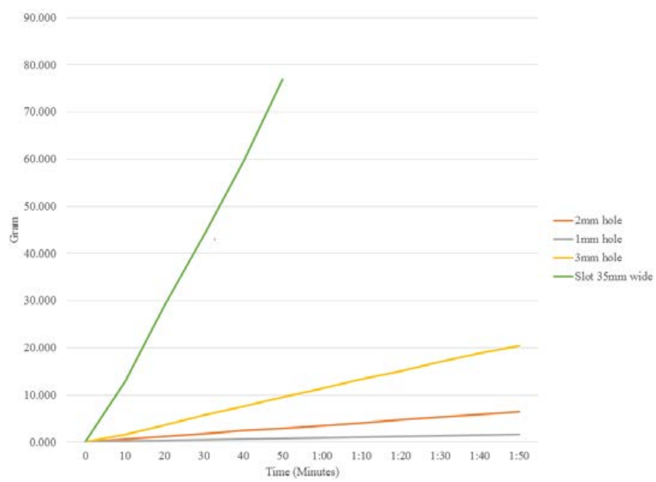


Figure 10 Establishing federate for various holes and slot

In preparation for first melt experiments, we established powder feedrates for 1 mm, 2 mm, 3 mm holes and a 35 mm slot. The feeding device was placed under a scale and powder was feed onto the scale. Time and weight were recorded as shown in Figure 10. Due to the limitation of the scale, time and weight resolution are coarse. It is planned to repeat these measurements with a more accurate and faster responding scale, but the established rates are consistent and can be reproduced in air and vacuum.

<u>Open Source Control</u>

Our machines are built with an open source controller, which allows the user to access data as required. With specific training, control loops can be modified for customization purposes. Programming of the machine will be in G-code style, allowing the use of various programs. Two levels of systems are provided:

Level 1 systems include beam controls only and the user can build their own vacuum system etc. Level 2 systems are turnkey and include all machine parameters and functions. This level runs on an EtherCat bus and interfaces with the machine through an I/O interface. This level includes a vision system that allows coaxial observation of the process which is an optional feature and can be ordered with the electron gun.

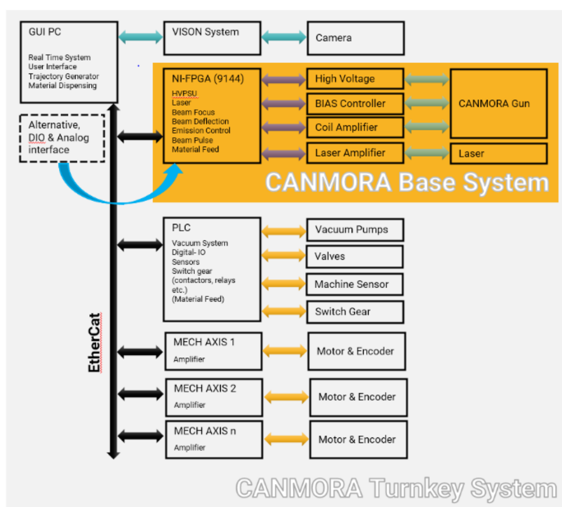


Figure 11 Open Source control concept

Summary and Conclusion

It is our objective to build a new generation of Electron Beam Additive Manufacturing machines which is open source allowing users to more completely understand their processing conditions. Further work will be required to scale this technology up to powder beds of 600 mm x 1200 mm x 400 mm and larger in size. Part of this scaling process is the newly developed powder feeder device, which allows point or line deposition of materials. Frequency modulation-based powder flow has been tested for atmospheric and vacuum pressures and is therefore useable for electron beam and laser applications alike. (Patent Pending)

We discussed EB melting process parameters and their impact on additive manufacturing. Vacuum pressures were reviewed and their impact on beam spot size has been explained. We examined the impact of high to low vacuum levels and their possible effect on beam and melt pool formation. Two types of cathode materials and their specific characteristics are shown. We presented electron trace simulations with several anode configurations, as well as their impact when optimized for beam current and beam focusing. This optimization may help to reduce cathode temperatures but may require higher bias voltages.

Acknowledgements

We would like to thank the University of British Columbia who allowed us to perform some of the experiments on their 150 kV EB machine, Figure 10; the machine was supplied by CANMORA in 2017.

Figure 12 UBC EB 150 kV machine

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