Electron Beam Coupling Efficiency in EBF^3

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Abstract

This study examines the coupling efficiency of the electron beam to a metal substrate in the Electron Beam Freeform Fabrication (EBF^3) system. EBF^3 is a type of additive manufacturing for metallic parts that uses an electron beam as an energy source. This type of additive manufacturing is of significant interest to NASA because of its ability to manufacture components for aircraft and spacecraft or repair parts while on long duration space missions. To make accurate models and computer simulations of the EBF^3 process, the electron beam coupling efficiency must be known. The coupling efficiency is defined as the percentage of energy from the electron beam that is transferred to the substrate material. By assuming a 100% coupling efficiency, the temperature change of a substrate material can be calculated based on material properties and the energy delivered from the electron beam. If the coupling efficiency is not 100%, a temperature change lower than this calculated value will be observed experimentally. This ratio of actual temperature change versus calculated temperature change will give the coupling efficiency of the electron beam to the substrate material. The initial intent of this study was to measure coupling efficiency for 316L Stainless Steel, Al 2219, and Ti-6Al-4V. After initial tests it appeared that processing parameters of beam focus, accelerating voltage, and beam power might have an effect on coupling efficiency. To further examine the effects of process parameters on coupling efficiency, tests focused on 316L Stainless Steel with additional testing done on Al 2219. Results of this study indicate a coupling efficiency of 60-70% in 316L Stainless Steel, a value that appears to be independent of process parameters. A simulation was done in COMSOL Multiphysics® that validates for comparison to the results of the 316L Stainless Steel coupling efficiency tests. Coupling efficiency for Al 2219 was found to be 40-60% and appeared to depend on process parameters in some tests. However, no trends were observed when comparing all tests to support this observation. The experimentally obtained values of electron beam coupling efficiency are lower than values reported in other literature and the values currently being used in modeling and simulation of the EBF^3 process. Having more precise coupling efficiency values will lead to more accurate models and simulations and ultimately improve the EBF^3 system.

Introduction

Electron Beam Freeform Fabrication (EBF^3) is a type of additive manufacturing for metallic parts that is of interest to NASA. The ability of EBF^3 to produce near net shaped parts is of value to aerospace manufacturing and long duration space flight. Tailoring of materials and material properties in EBF^3 also makes this process of interest to the aerospace industry [1]. To fully understand the design space available to the EBF^3 method, accurate simulations and models of the entire process must be made. Coupling efficiency is an important aspect of an accurate simulation or model and is a measure of how much energy from the electron beam is being put into the substrate. Without an accurate value of coupling efficiency, simulations and models will not represent what is actually occurring in the EBF^3 process. The goal of this study was to determine the electron beam coupling efficiency in the EBF^3 process for 316L Stainless Steel, Al 2219, and Ti-6-4. Results from previous studies on electron beam coupling efficiency indicate values of 80-95% efficiency [2-4]. Along with determining the coupling efficiency, this study would hope to also analyze the affects of process parameters of accelerating voltage, beam focus, and beam power on coupling efficiency.

Results and Discussion

After initial testing on 316L Stainless Steel it was thought that the process parameters being examined were affecting the value of coupling efficiency. At this point a decision was made to further investigate this observation and perform repeated tests on 316L Stainless Steel rather than examine several materials. Once a confident value of coupling efficiency in 316L Stainless Steel had been determined, tests would be performed on Al 2219. Results indicate that the electron beam coupling efficiency for 316L Stainless Steel is 60-70%. Examination of the results indicates that coupling efficiency does not appear to increase with a raster beam and a higher accelerating voltage or alternatively decrease with a defocused beam with a lower accelerating voltage. These results indicate that coupling efficiency in 316L Stainless Steel is 60-70% and is independent of the process parameters examined.

To compare the results of 316L Stainless Steel electron beam coupling efficiency tests, a simulation of the experiment was made using COMSOL Multiphysics. A test done in the EBF^3 system using a 1500 W 30 kV raster beam found a coupling efficiency value of 72.7%. This coupling efficiency value meant that the plate absorbed only 1090 W of the 1500 W delivered from the electron beam gun. Running a simulation and putting 1090 W into a plate should result in a similar temperature profile to the 1500 W test with 72.7% coupling efficiency. After comparing the simulated temperature profile and the experimental temperature profile, very good agreement is observed between the two. The ability to closely match simulation results to experimental results indicatess that the electron beam coupling efficiency in 316L Stainless Steel can confidently be reported as 60-70%.

After running tests, the electron beam coupling efficiency in Al 2219 was found to be 40-60%. From previous observations during EBF^3 experiments, it was believed that coupling efficiency in Al 2219 was dependent on the process parameters used. However, from analysis of the data no trends are apparent to indicate that process parameters are affecting coupling efficiency. The inability to match the data to observations with other Al 2219 experiments indicates that more tests should be made. Additional testing on Al 2219 could accomplish several things. Most importantly, more tests would indicate whether electron beam coupling efficiency in Al 2219 was affected by accelerating voltage or beam focus. Additional testing would also achieve a more confident value of electron beam coupling efficiency in Al 2219.

Conclusion

EBF^3's ability to produce near net shaped parts could reduce launch mass by replacing potentially unused spare parts with a lower mass of wire. Without being able run simulations of the EBF^3 process many experiments must be run to determine what is happening during the process. This becomes very time and economically inefficient. Simulation however, is an efficient alternative to experiment if it produce accurate results. One of the most important aspects to these simulations is being able to accurately represent the amount of energy from the electron beam that is absorbed by the substrate material, or the electron beam coupling efficiency. This study found the electron beam coupling efficiency in 316L Stainless Steel to be 60-70%. To compare the experimental results, simulations were made using COMSOL Multiphysics. The experimental results match closely to the simulation results indicating that an reasonable value of coupling efficiency has been determined. This value of electron beam coupling efficiency is much lower than values reported in previous coupling efficiency studies, increasing the significance of these results[2-3]. Unlike initial thoughts, this value does not appear to depend on process parameters of accelerating voltage or beam focus. Attempts were also made to determine the electron beam coupling efficiency in Al 2219. Results did not prove to be conclusive enough to give a confident value of coupling efficiency in Al 2219. However, additional testing can be done with Al 2219 and should produce more consistent results. The ability to now include accurate coupling efficiency values in models and simulations will only make the EBF^3 process better and more efficient.

Acknowledgments

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Introduction

Electron Beam Freeform Fabrication (EBF^3) is a type of additive manufacturing for metallic parts that is of interest to NASA. The ability of EBF^3 to produce near net shape parts make it advantageous system to have on a long duration space flight. This ability could eliminate the need to take spare tools or parts during a space mission, ultimately, reducing total weight and mission costs.

To fully understand the design space available to the EBF^3 method, accurate simulations and models must be created. These simulations reduce the cost and time associated with running numerous experiments to gain a better knowledge of what is happening during the EBF^3 process. An accurate simulation requires an understanding of the amount of energy transferred from the electron beam to the substrate material, or the electron beam coupling efficiency.

EBF^3 Background

- Machine consists of an electron beam gun and dual wire feeder housed inside a vacuum chamber
- Capable of converting a CAD drawing into a 3D metallic part
- Electron beam is focused and melts incoming wire and creates melt pool on substrate material
- Beam moves and molten pool area solidifies creating a layer of new material on the substrate
- In this fashion a 3D part is built layer by layer

Top: EBF^3 during a deposit
Bottom: Parts that have been fabricated using EBF^3 [3]

Goals

1. Determine electron beam coupling efficiency in 316L Stainless Steel
2. Determine if electron beam coupling efficiency is affected by process parameters of accelerating voltage, beam focus, and beam power

Experimental Procedure

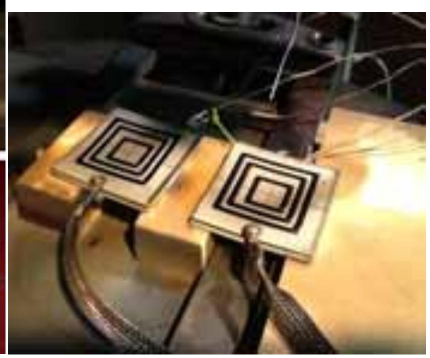
- Can determine electron beam coupling efficiency through calorimetric method

$$\eta = \frac{m_s \, c_p \, \Delta T}{P \, t} \qquad \text{(Eq. 1)}$$

- Experiment occurs in a vacuum chamber so typical calorimetric method cannot be used
- 3" x 3" x ¼" plates of 316L Stainless Steel and Al 2219
- Square beam paths were used since simulation showed that circular passes would not distribute heat to corners of the plate
- Accelerating voltage was set to 30 or 40 kV, a typical operating value
- Beam focus was either a tightly focused Raster beam or slightly defocused diffused beam
- Low, Medium, and High powers were used during testing
  - Low: Plate was heated with out melting
  - Medium: Just above melting threshold so only minimal melting occurred
  - High: Significant level of melting occurred on surface of the plate
- Thermocouples attached to bottom center and bottom edge of plate to track temperature
- Ratio of experimental temperature change to calculated temperature change or by placing the observed temperature change into Equation 1 will calculate coupling efficiency

Results

- 316L Stainless Steel Coupling Efficiency was determined to be 60-70%
- Much lower than the 80-95% reported in previous studies [4-5]
- These results indicate that coupling efficiency in 316L Stainless Steel is independent of the process parameters examined in this study
- Simulation of experiment made in COMSOL Multiphysics®
- Simulation compares well to experimental data giving confidence in electron beam coupling efficiency value in 316L Stainless Steel



Above: Experiment setup to determine electron beam coupling efficiency. Plates were placed on ceramic to eliminate any heat loss through conduction. Since tests were done in a vacuum, radiation is the only source of heat loss. Grounding straps were then attached to the plates to make them electrically conductive.

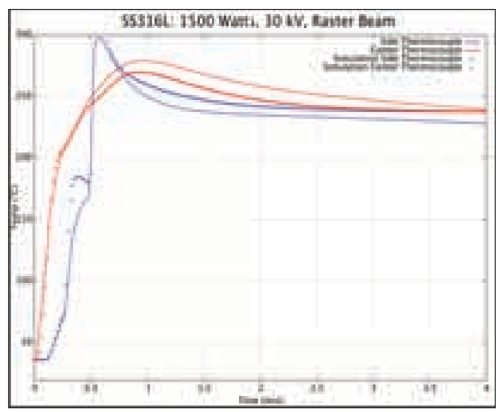


Fig. 1. Temperature profile of a plate during a test. Test was done using a 1500 W Raster beam with an accelerating voltage of 30 kV. This test resulted in a 72.7% electron beam coupling efficiency. Figure 1 also shows a simulation putting a similar amount of energy into a plate. Simulation did not include heat loss through radiation so some disagreement is expected. General shape of curves is a very close match supporting experimental results in 316L Stainless Steel.

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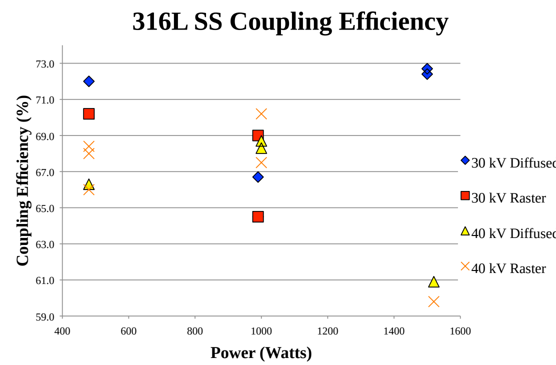

Experimental Error

- Is experimental error present since we see different results than previous studies?
- Is the beam producing the correct power?
  - If beam power is lower than expected lower coupling efficiency values would be observed
- Ceramic block was warm after some tests
  - This would indicate that heat is being lost to the ceramic
- If thermocouples were not attached properly inaccurate temperature could be read
  - Mostly an issue in Al 2219 testing when thermocouples were held on with kapton tape
- Exact location of thermocouples was important since large thermal gradients were present in plates

Conclusions and Future Work

- Successfully determined electron beam coupling efficiency in 316L Stainless Steel
- Further testing with Al 2219 to achieve conclusive results and determine accurate value of coupling efficiency
  - Improve thermocouple attachment in Al 2219 tests
- Use simulation to match results of Al 2219 testing
- Data collection with thermocouples/acquisition software was sometimes inconsistent
  - Improve the consistency of data collection
- Examine coupling efficiency in Ti-6

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The author would like to thank his mentor, Bill Seufzer, for his guidance during this project as well as running the simulations to compare experimental results too. The author would also like to thank all of the members of the EBF^3 team at NASA Langley Research Center for their support and advice.