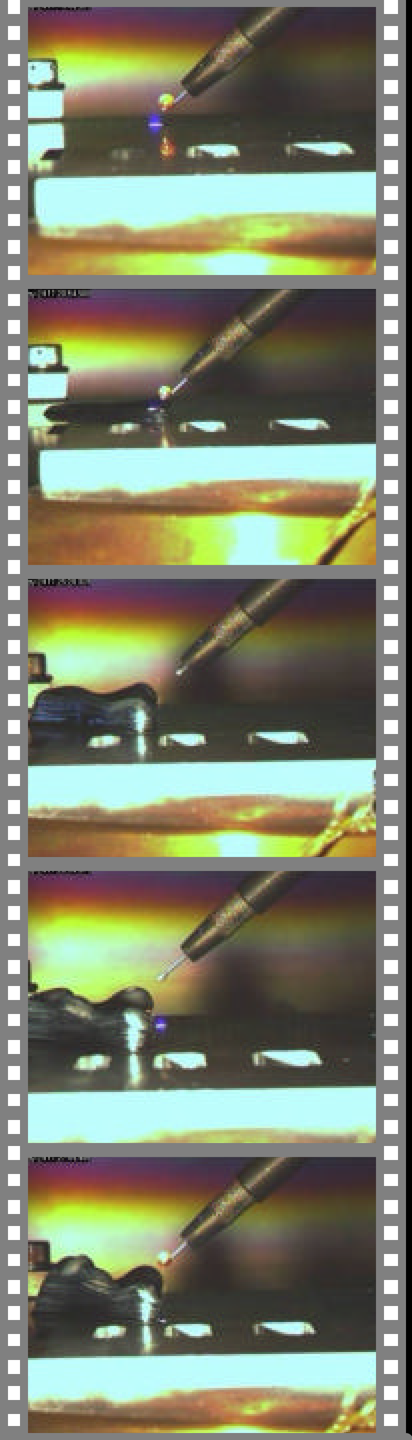

Electron Beam Freeform Fabrication in the Space Environment

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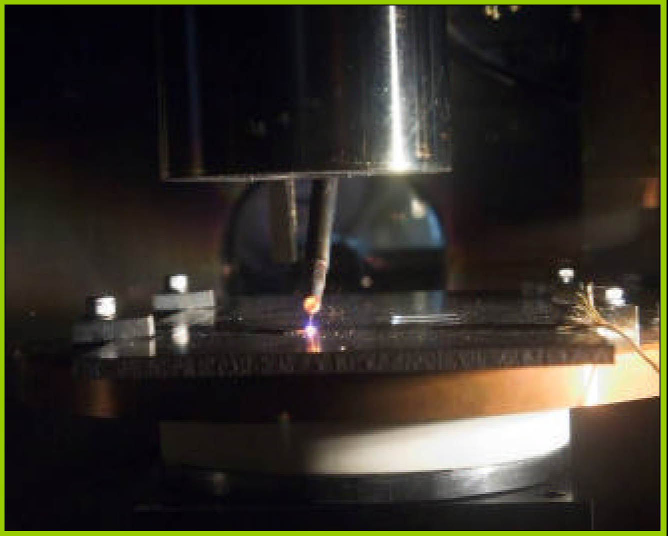
Electron Beam Freeform Fabrication in the Space Environment

<u>**Outline**</u>

- **Background**
- **Electron beam freeform fabrication (EBF^3) system**
- **Microgravity test objectives**
- **Effects of microgravity on EBF^3**
- **Summary**



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Spare Parts for Long Duration Space Missions

- Future long duration human space missions will be challenged by mass and volume constraints for spare parts
- Use of solid freeform fabrication processes could reduce the need for pre-manufactured spares by generating parts as needed
- Electron beam deposition using wire feedstock offers high energy and feedstock efficiency

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- Key issue to be investigated is the effect of microgravity on the process

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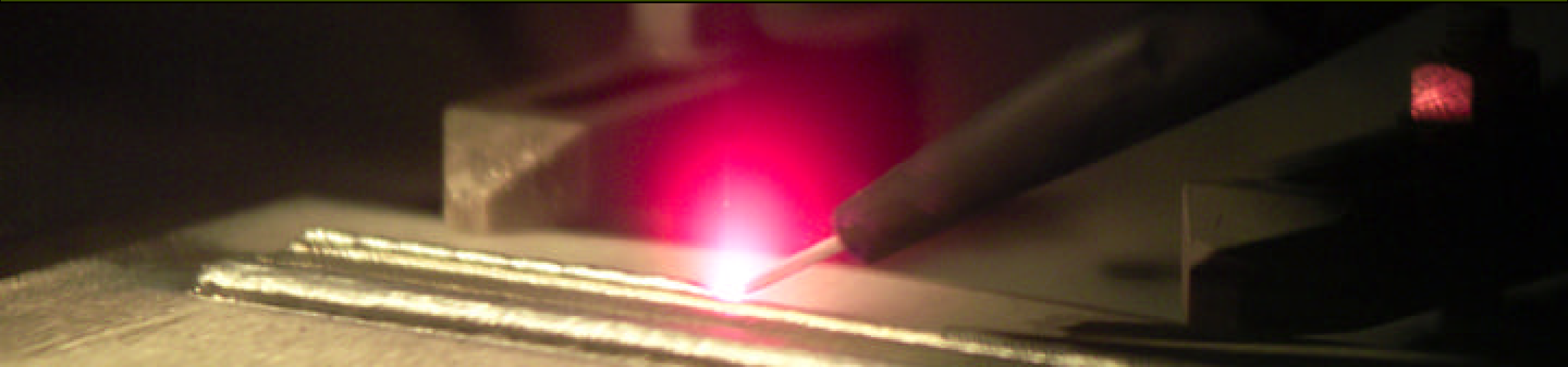
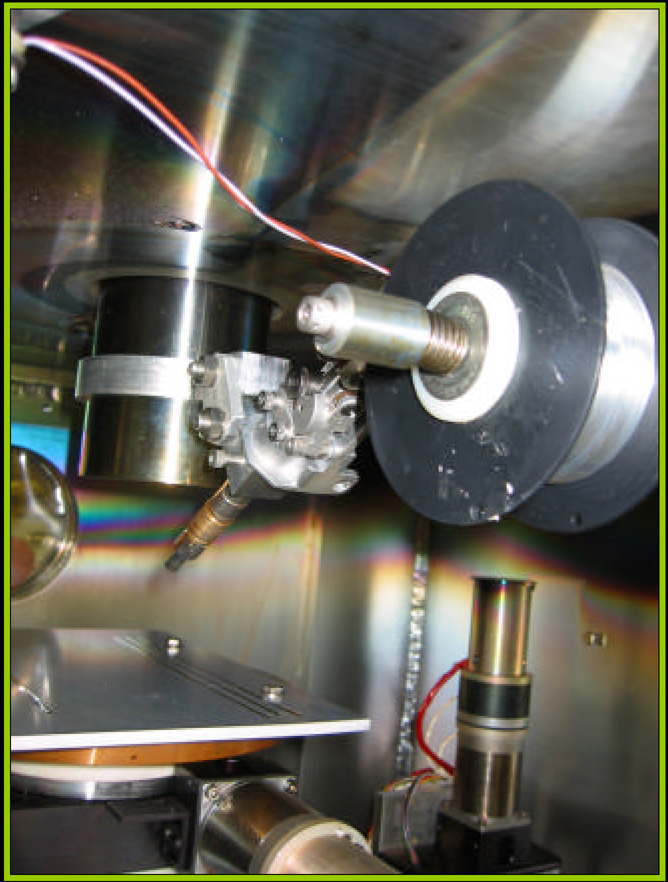
Electron Beam Freeform Fabrication (EBF^3) Process Description

- Layer-additive process to build parts using CNC techniques
- Electron beam melts pool on substrate, metal wire added to build up part
- Material properties similar to those of annealed wrought products
- ~100% dense, structural metallic parts produced directly from CAD file without molds, tooling, or machining
- Secondary processing also possible with reconfigured beam



Portable Electron Beam Freeform Fabrication System at NASA LaRC



Portable EBF^3 system design:

- 3-5 kW, focusable EB gun
- 4-axis motion system with 12 in. x 12 in. x 8 in. build envelope
- 0.03-0.045 in. dia. wire feeder

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Electron Beam Freeform Fabrication in the Space Environment

Objective:

- Demonstrate EBF^3 process is possible in 0-g
- Understand EBF^3 process kinetics and driving forces in 0-g environment for developing control system

Approach:

- Conduct ground based tests and simulated 0-g tests on portable EBF^3 system
- Vary deposition parameters such as translation directions, standoff distance, wire feed rates to
- Compare results from ground-based tests and 0-g tests for consistency and differences in bead geometries and microstructures

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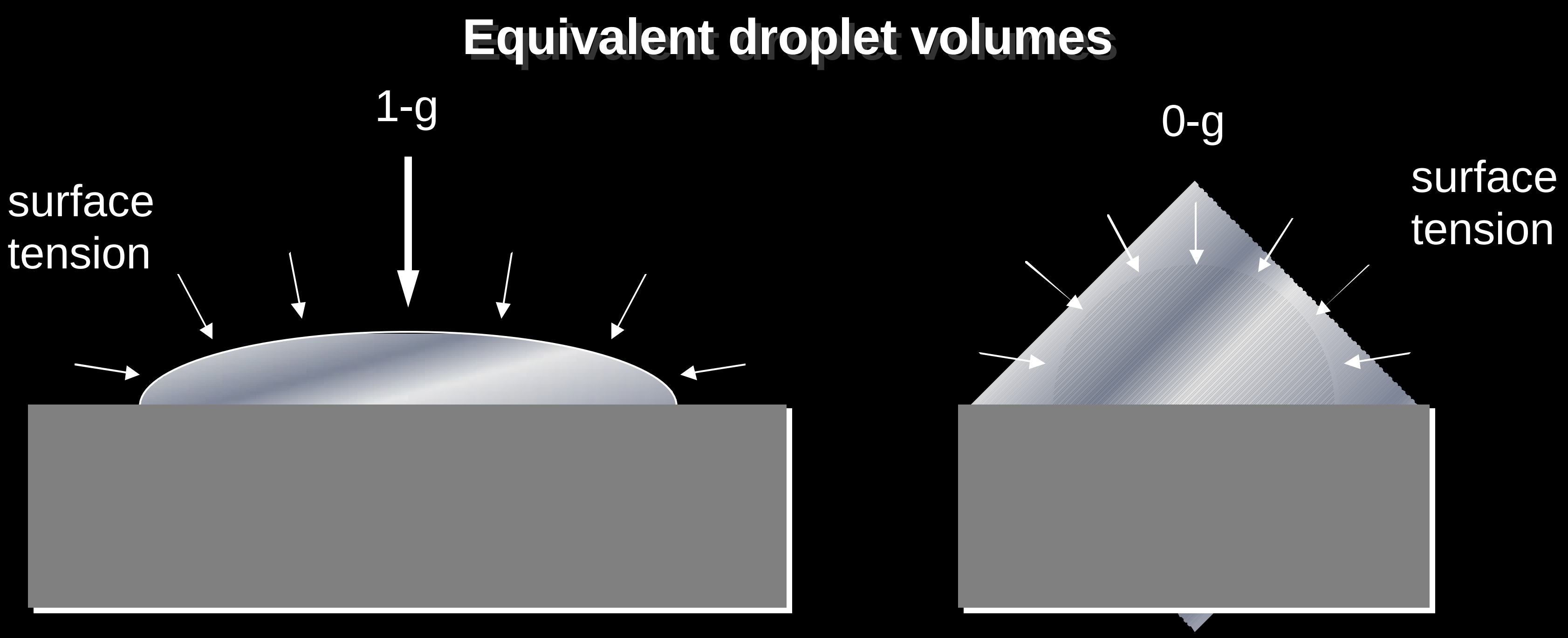
Effect of Gravity on Surface Tension



- **Body forces eliminated – surface tension dominates**
  - **Alteration of bead cross-section may affect surface topography of finished part**
  - **Influence on closed-loop control target values**
- **Possible influence on microstructure of solidified deposit**

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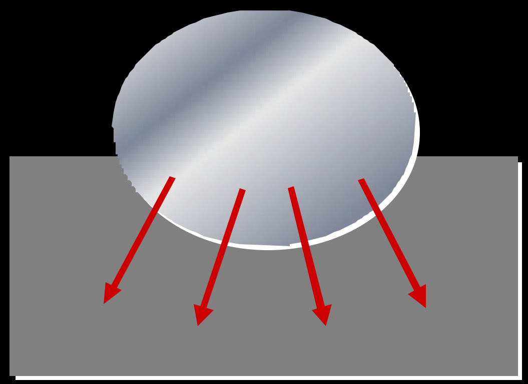
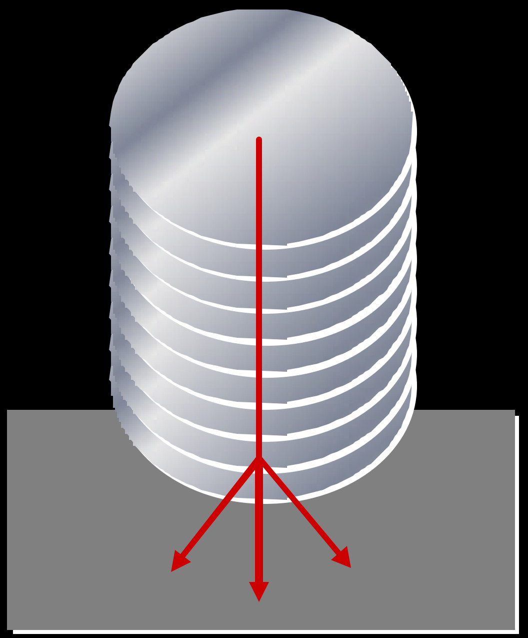
Effect of Deposit Height on Cooling Path





- **First layer – cooling rate dominated by path through substrate**
  - **Quick cooling**
- **Many layers – cooling rate dominated by path through prior build**
  - **Slower cooling, deposit temperature increases causing deposit width to increase**

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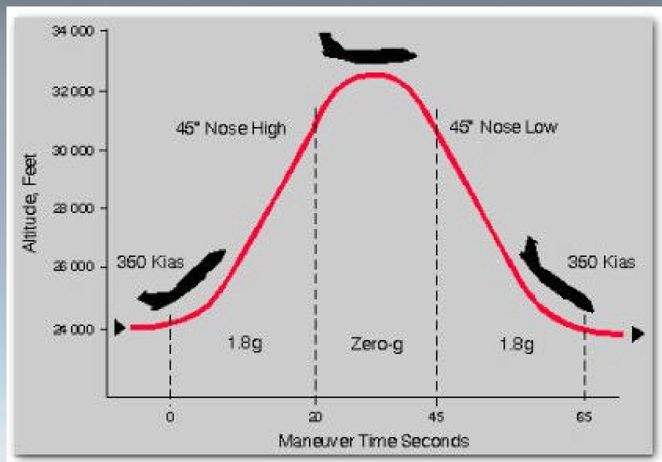
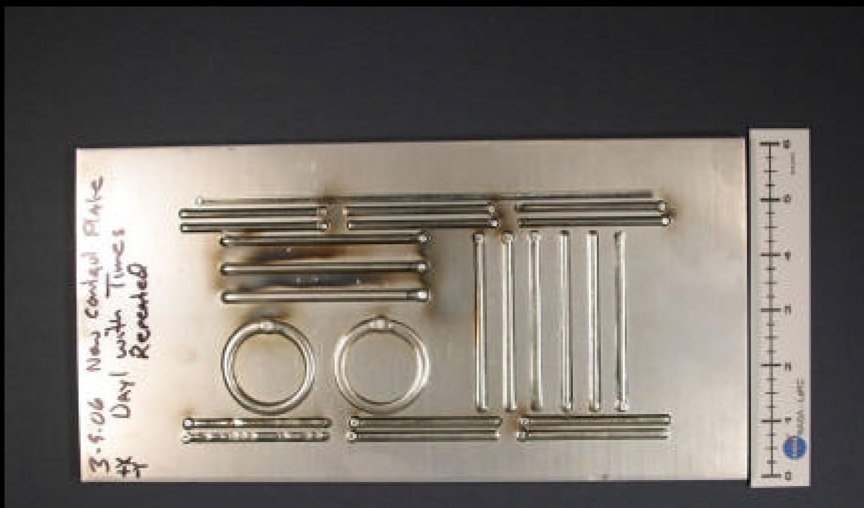
Microgravity Testing Aboard JSC's C-9

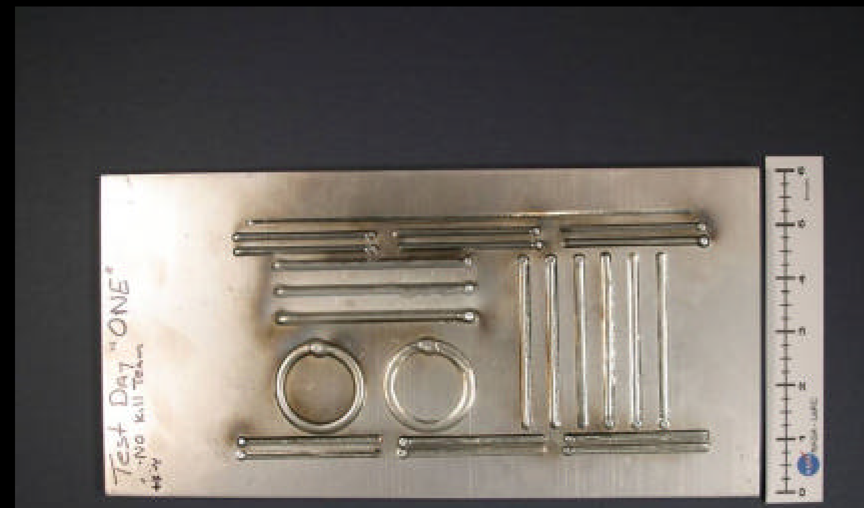


- **C-9 Capabilities**
  - **10^{-2}-g, Lunar-g, Martian-g capability**
  - **15-20 second duration for 10^{-2}-g, longer for partial-g**
  - **1.8-g during pullout**
  - **40 parabolas per flight typical**

Typical Test Flight Plates



1-g plate



0-g plate

- **Series of builds 1-4 layers high**
- **Lines built in different directions (+/- X & Y)**
- **No difference in deposit height & width between 0-g and 1-g**
- **Cooling paths are dominated by baseplate**

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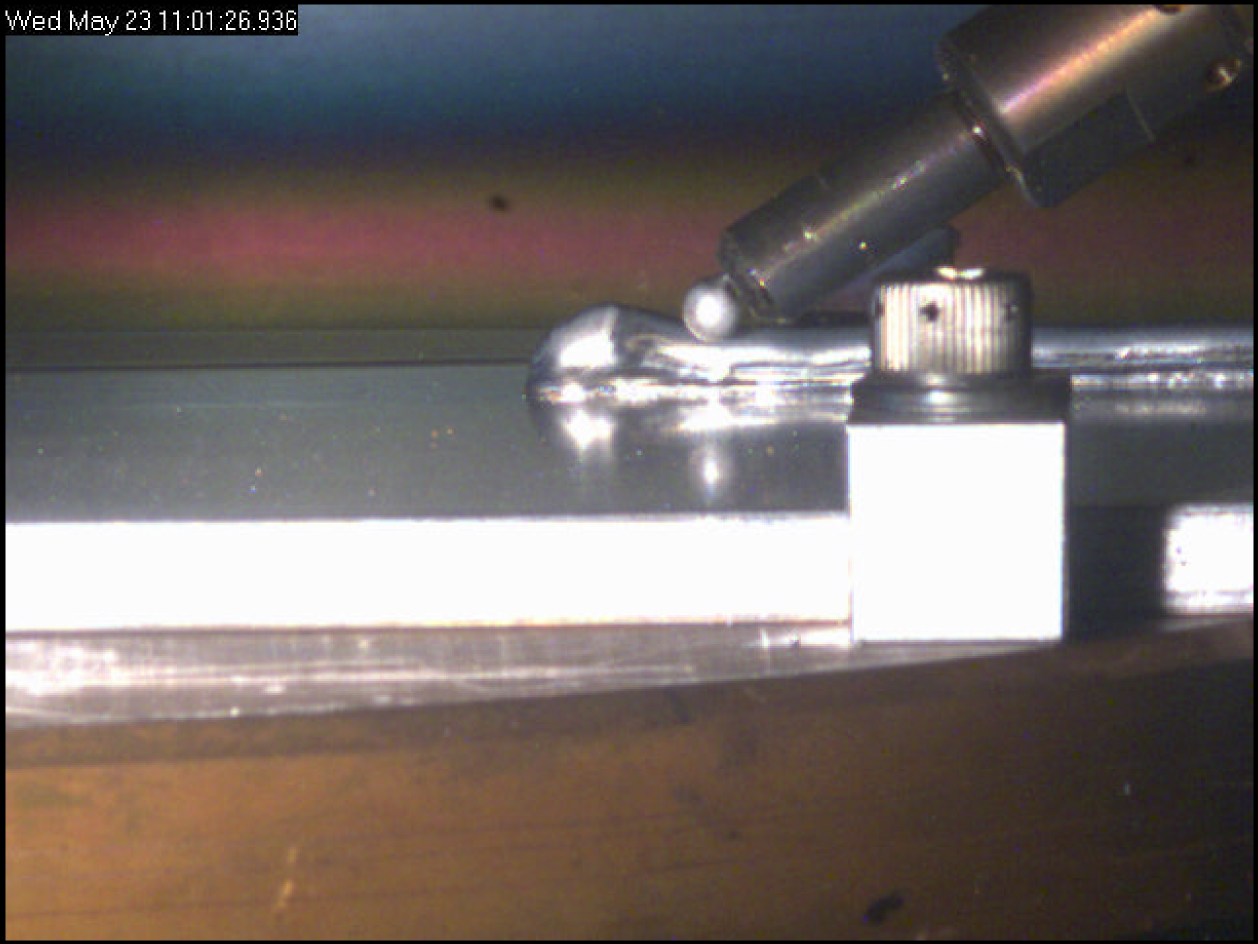
Direction and Height Trials for Process Control

Wire Fed into Leading Edge of Molten Pool



- Wire fed into leading edge is easiest to control
- Standoff distance increasing slightly along length of deposit

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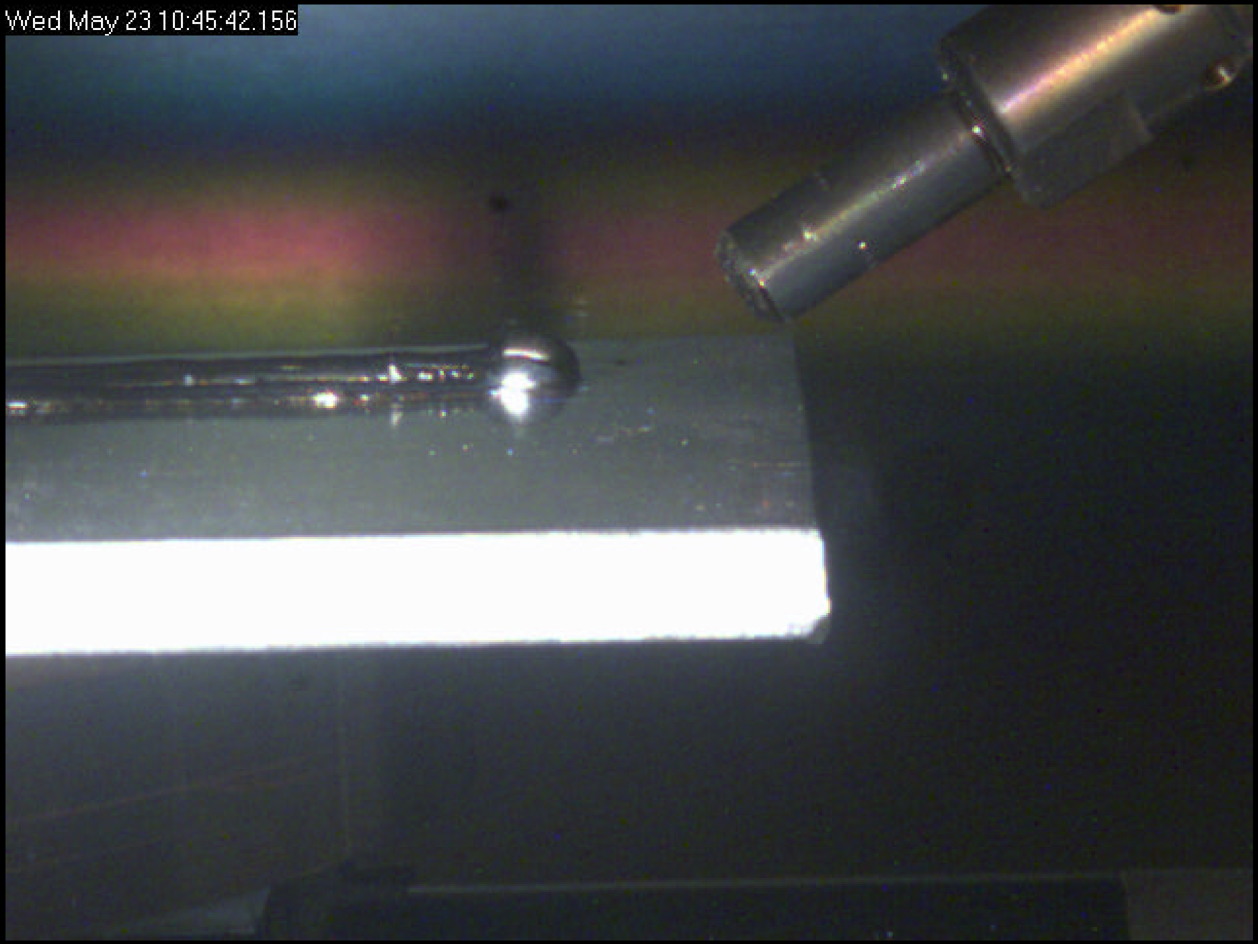
Direction and Height Trials for Process Control
Wire Fed into Trailing Edge of Molten Pool



- Wire fed into trailing edge pushes deposit in front of wire tip
- Standoff distance increasing slightly along length of deposit

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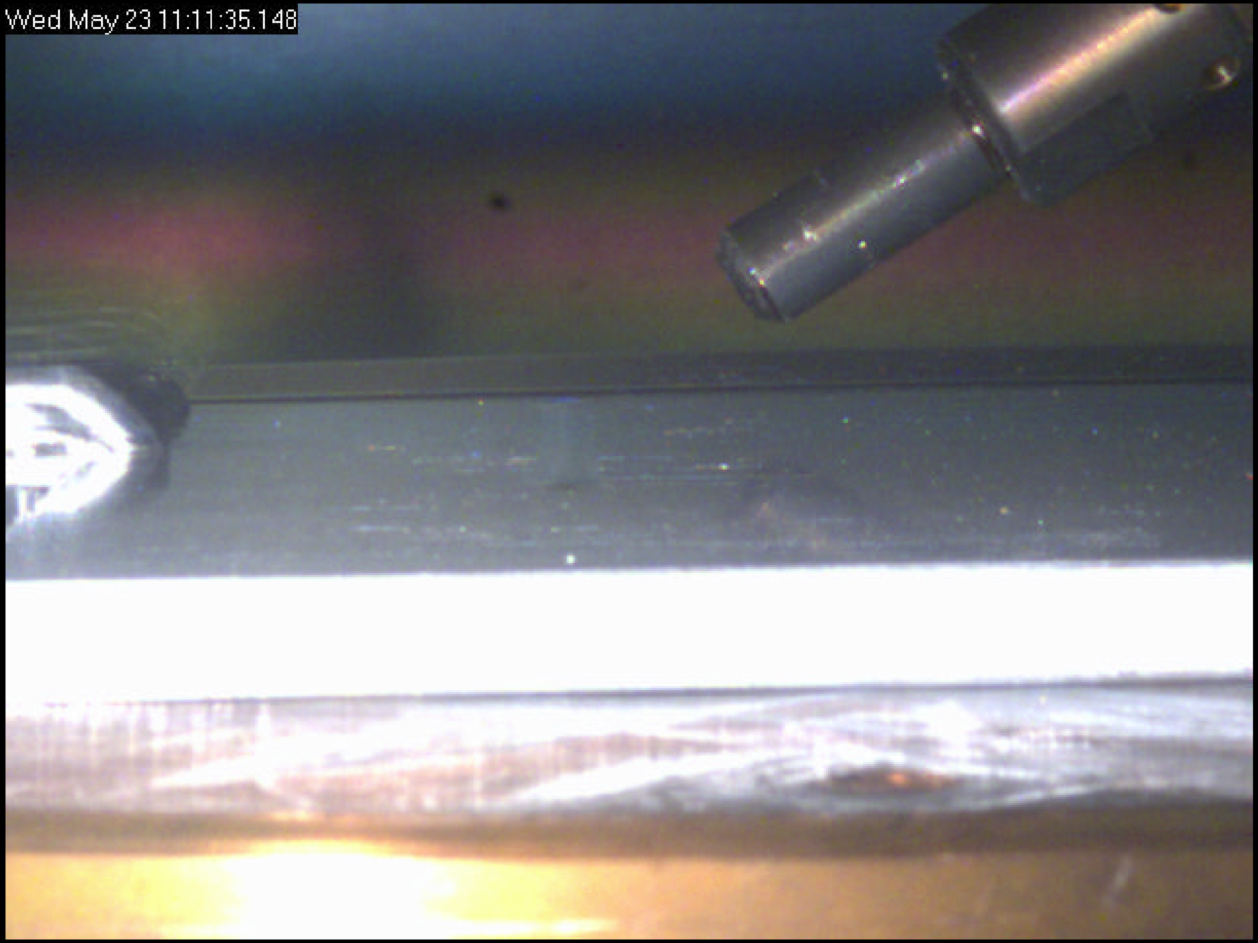
Direction and Height Trials for Process Control

Wire Fed into Side of Molten Pool



- Wire fed into side pushes deposit in front of wire tip
- Standoff distance increasing slightly along length of deposit

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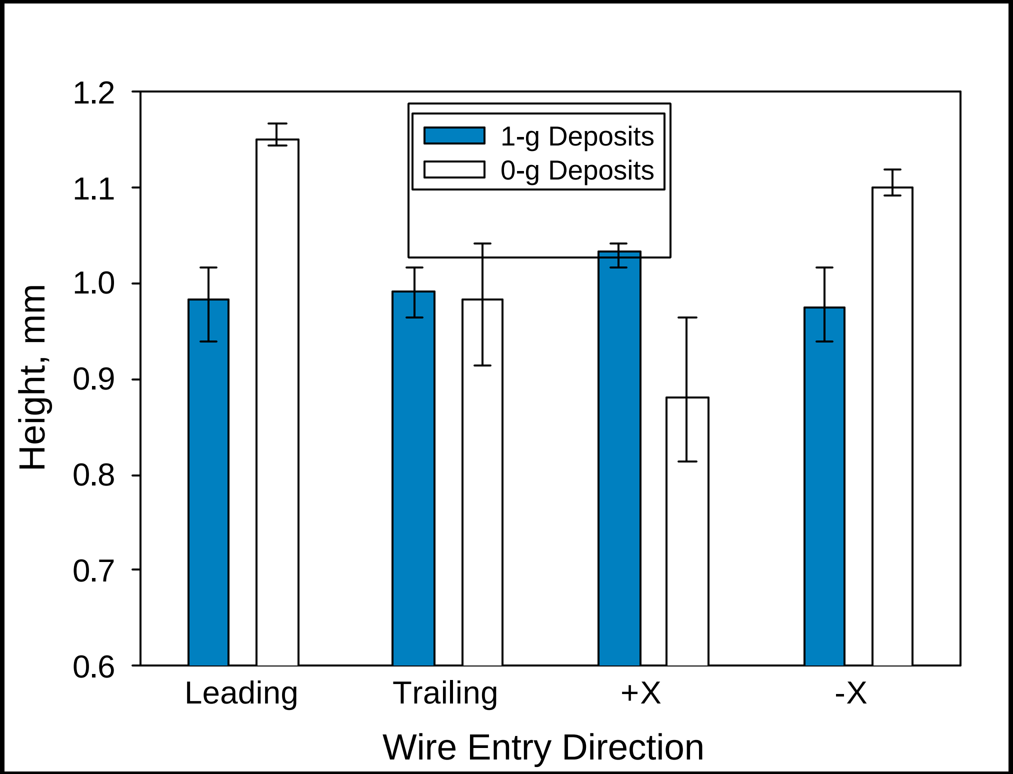
Effect of Wire Entry Direction into Molten Pool



- **Wire entry direction into molten pool affects bead shape more in 0-g than in 1-g**
- **No clear trend in height with wire entry direction**

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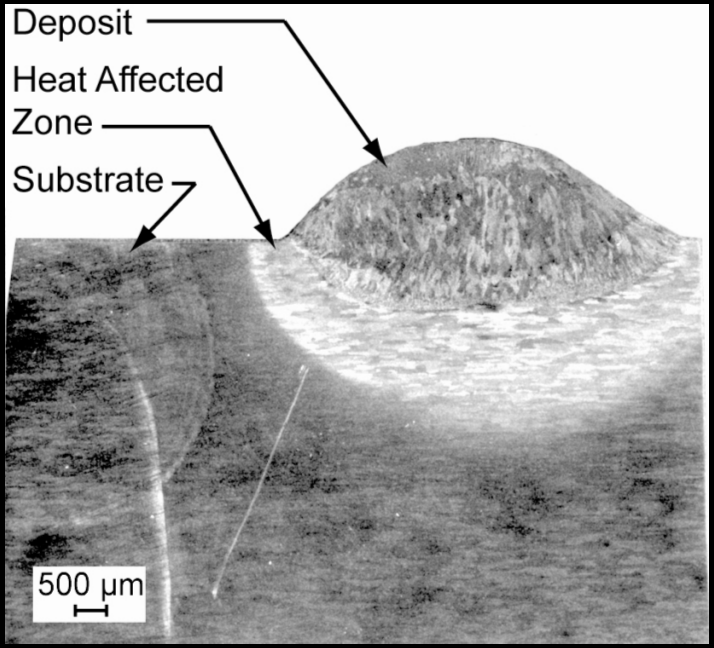
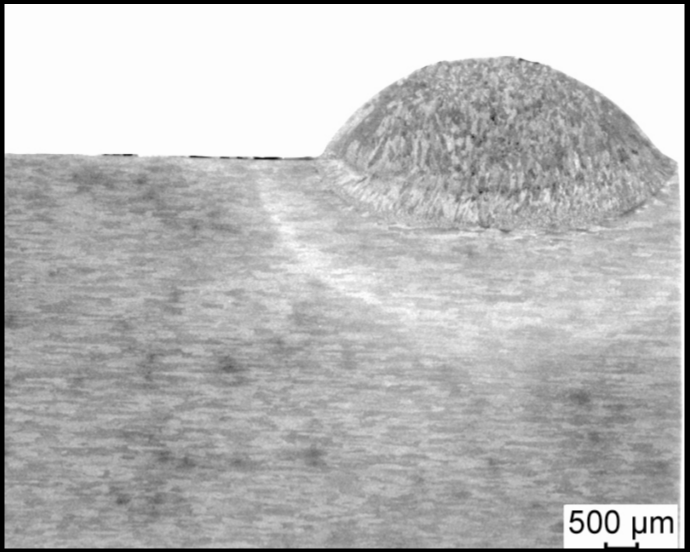
Microstructure of Single Layer EBF^3 Deposits



0-g deposit



1-g deposit

- **Typical microstructure seen in EBF^3 deposits**
- **Fine grain cast aluminum structure**
  - **Columnar grains nucleating from bottom of molten pool**
- **No evidence of porosity**

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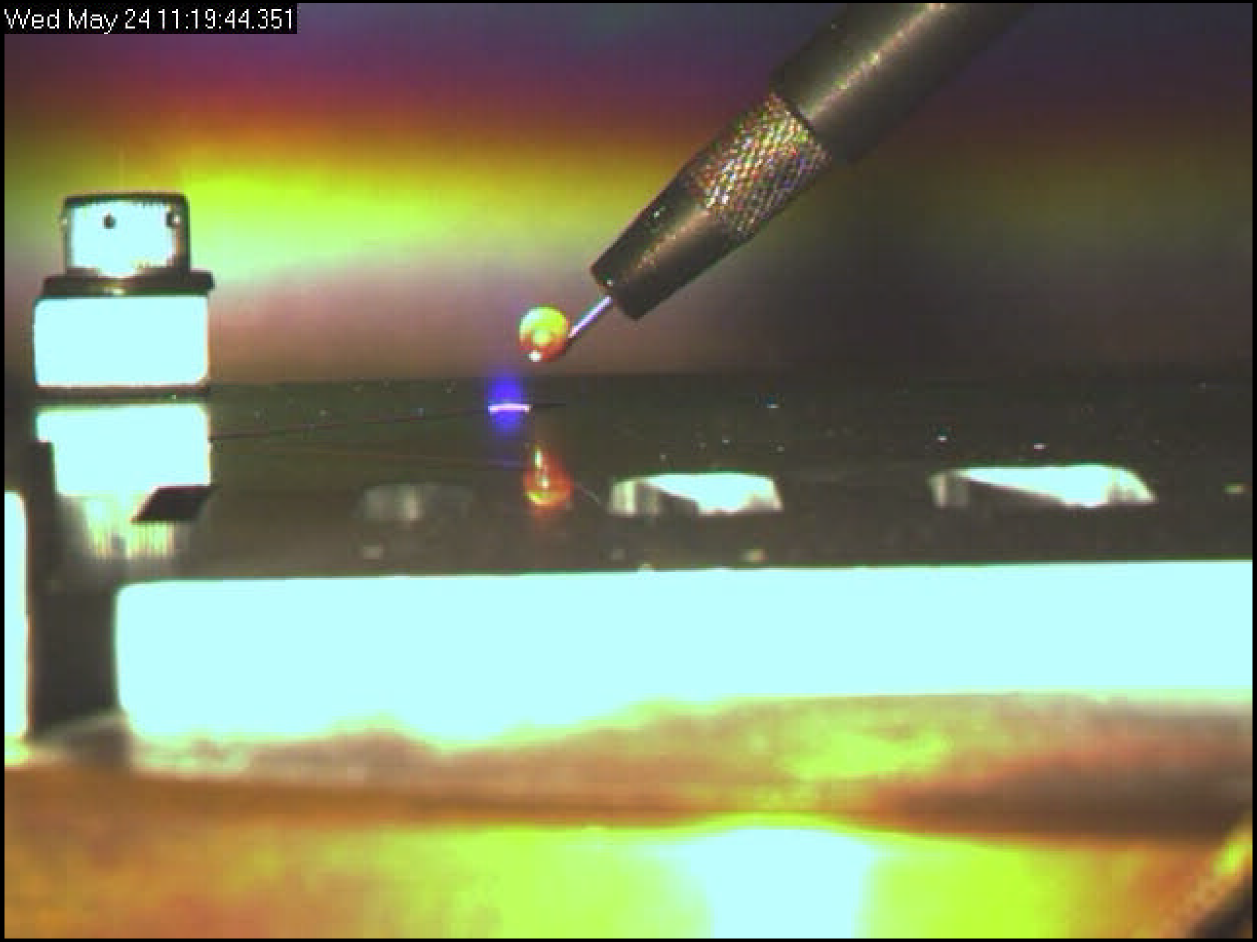
0-g Deposit with Incorrect Standoff Distance

Chevron, Layer 1



- Started too high off substrate, molten ball adheres to wire tip
- Upon contact with plate, wetting forces overcome surface tension

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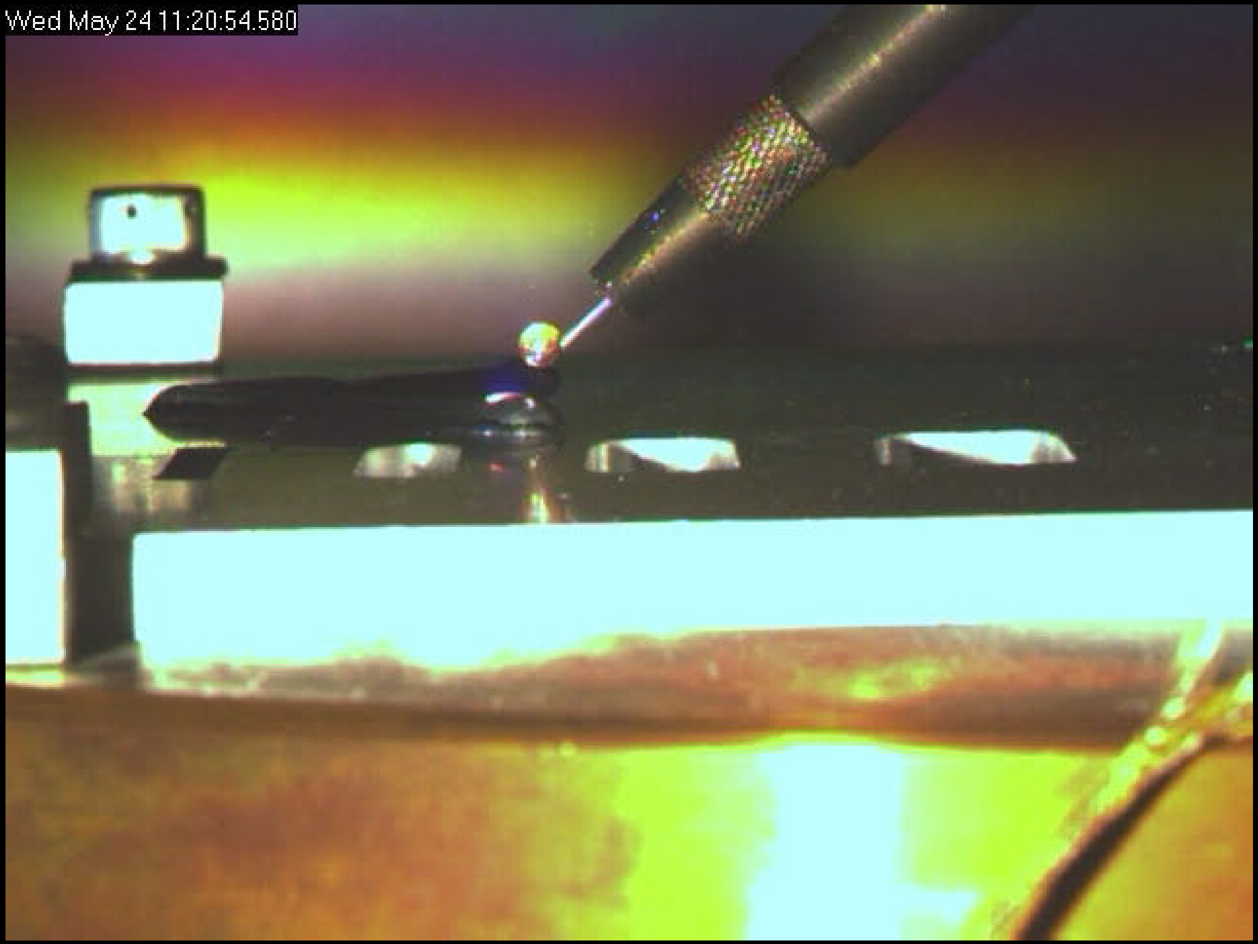
0-g Deposit with Incorrect Standoff Distance

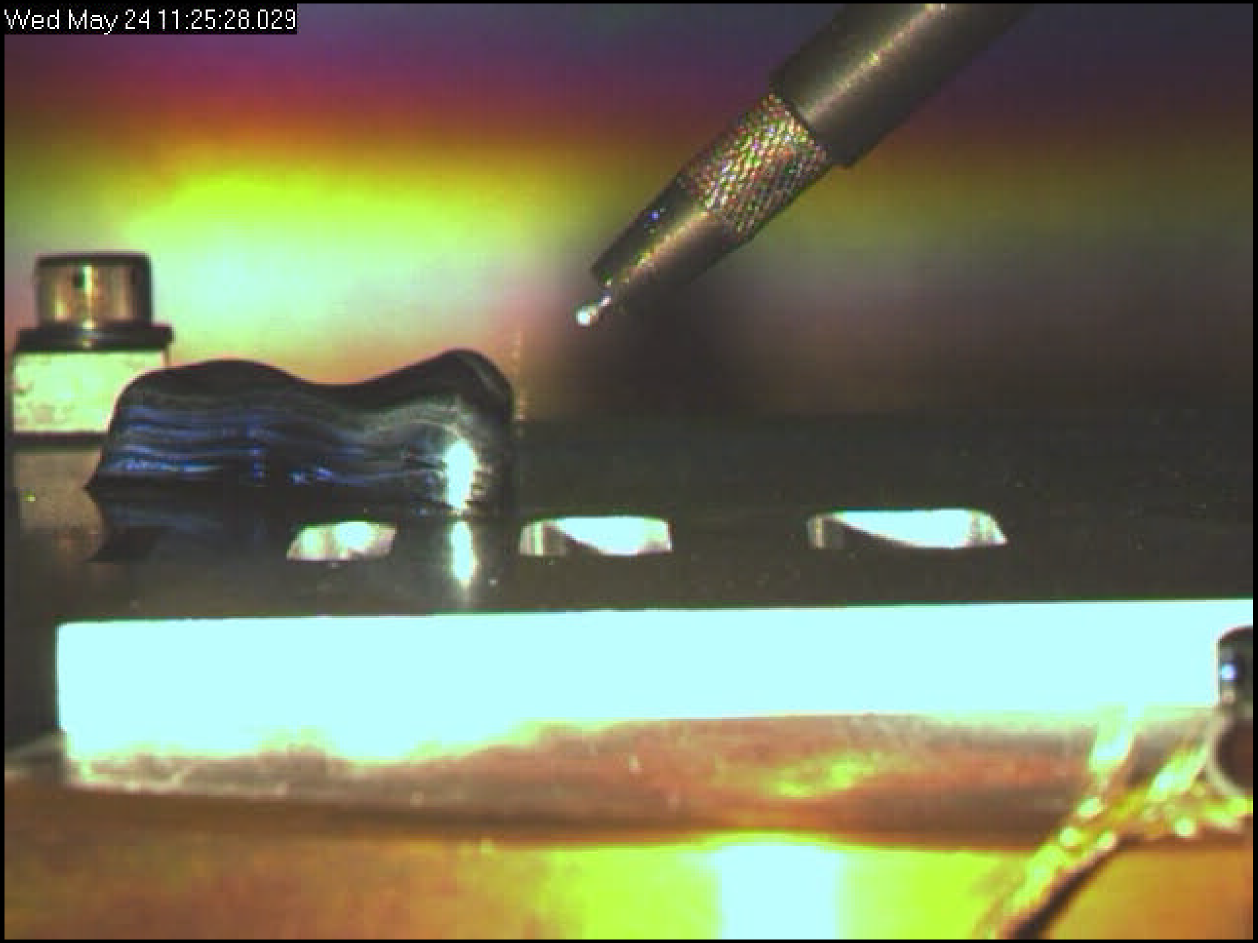
Chevron, Layer 2



- **Manual height correction between layers not large enough**

0-g Deposit with Incorrect Standoff Distance

Chevron, Layer 6



- **After several more layers, height errors become cumulative**

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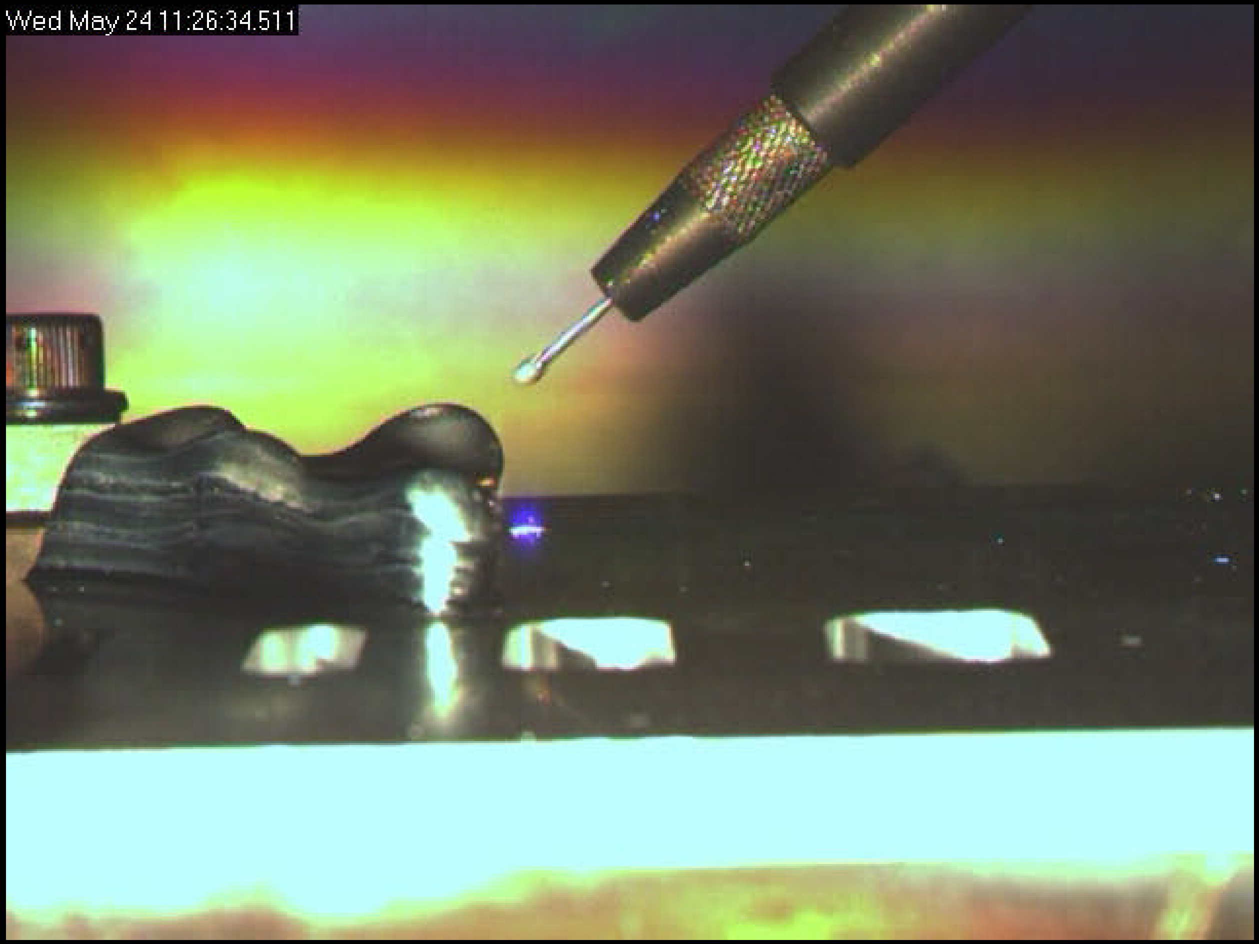
0-g Deposit with Incorrect Standoff Distance
Chevron, Layer 7



- Balls forming in 0-g are larger than drips in 1-g
- Size of molten balls depends on separation distance between plate and wire tip

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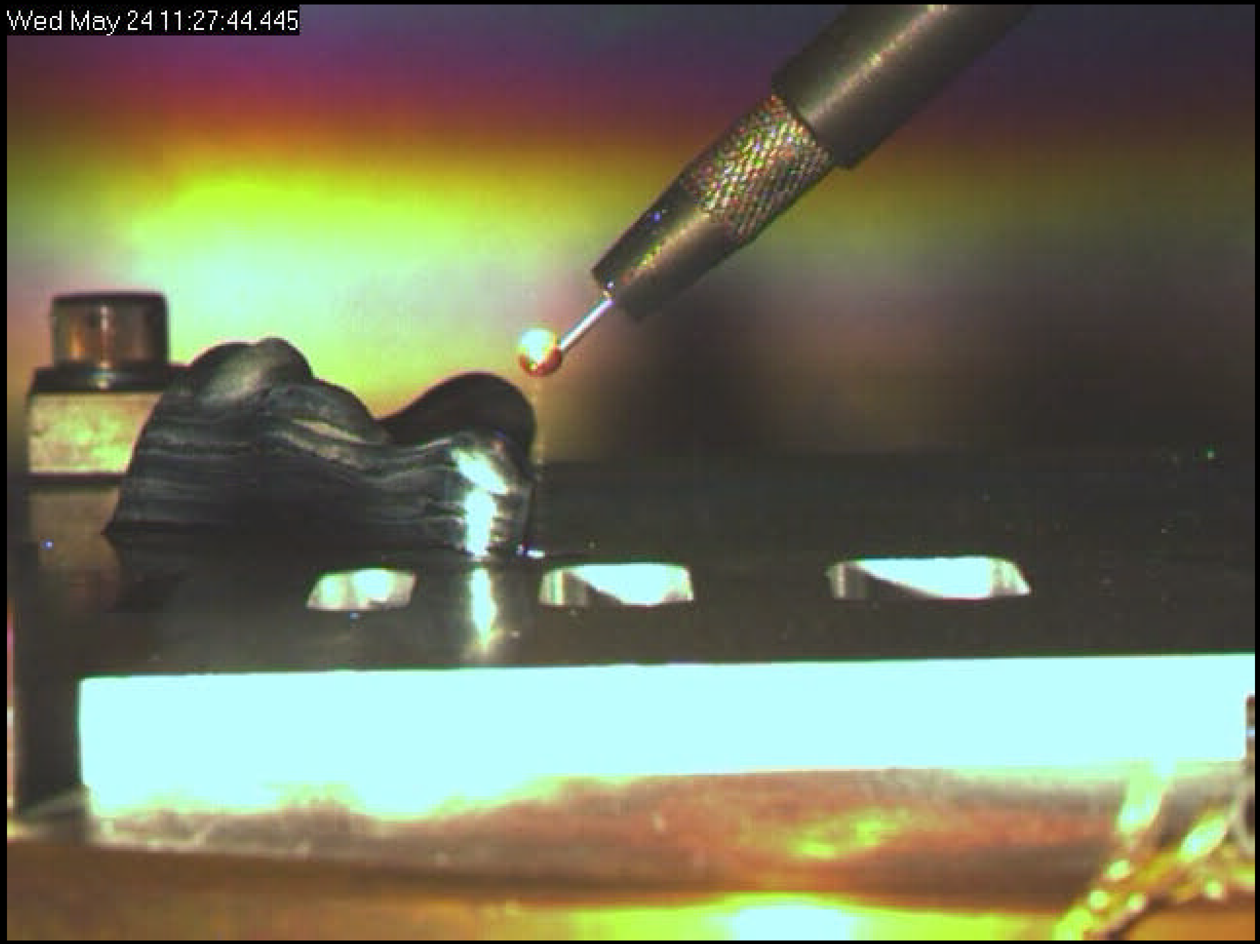
0-g Deposit with Incorrect Standoff Distance

Chevron, Layer 8



- **Attach/detach heights useful for developing height control**
- **Maintaining correct distance more important to process control in 0-g**

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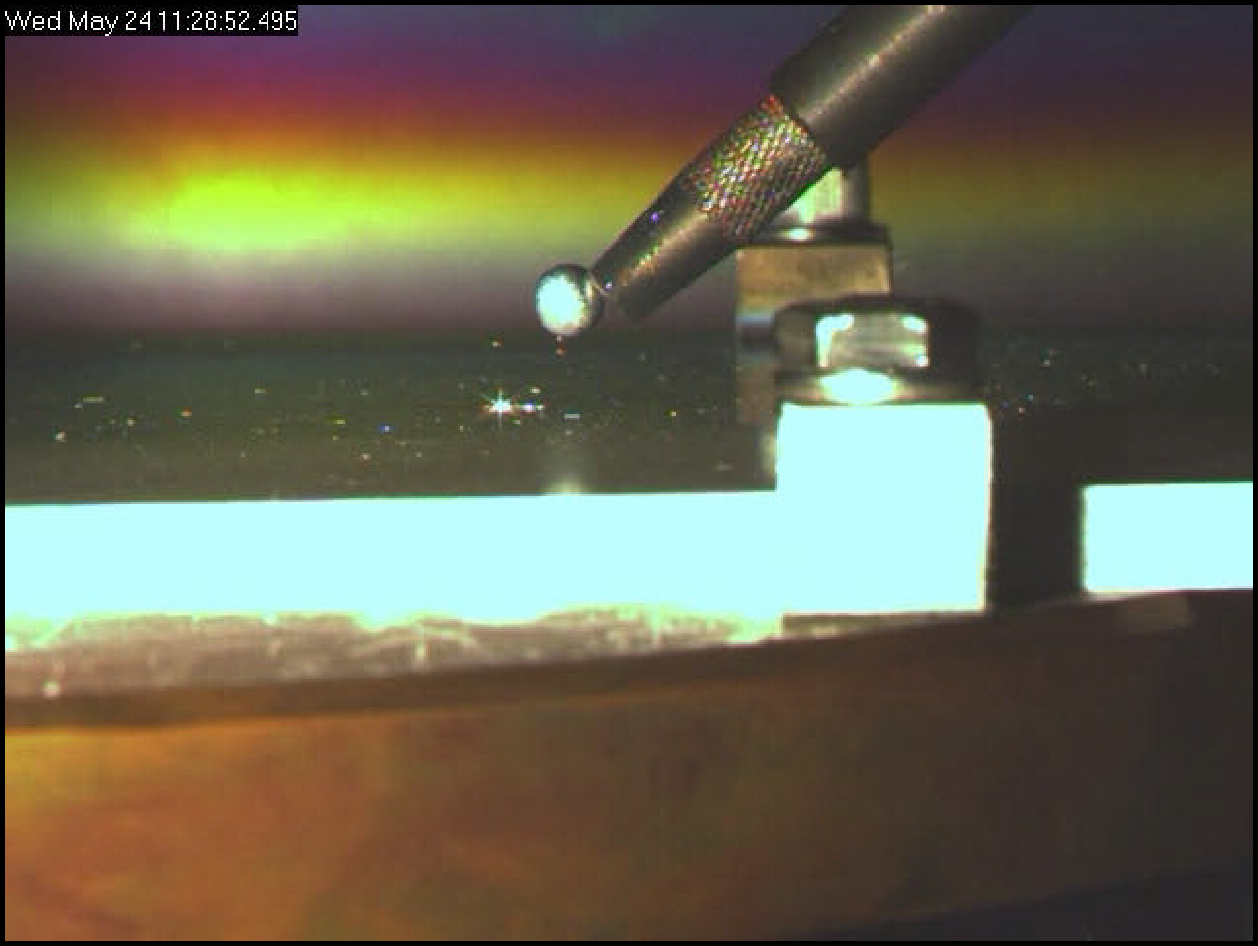
Successful Demonstration of EBF^3 in 0-g
Circle, Layers 1 & 2



- **Manual height correction helped maintain contiguous deposit**

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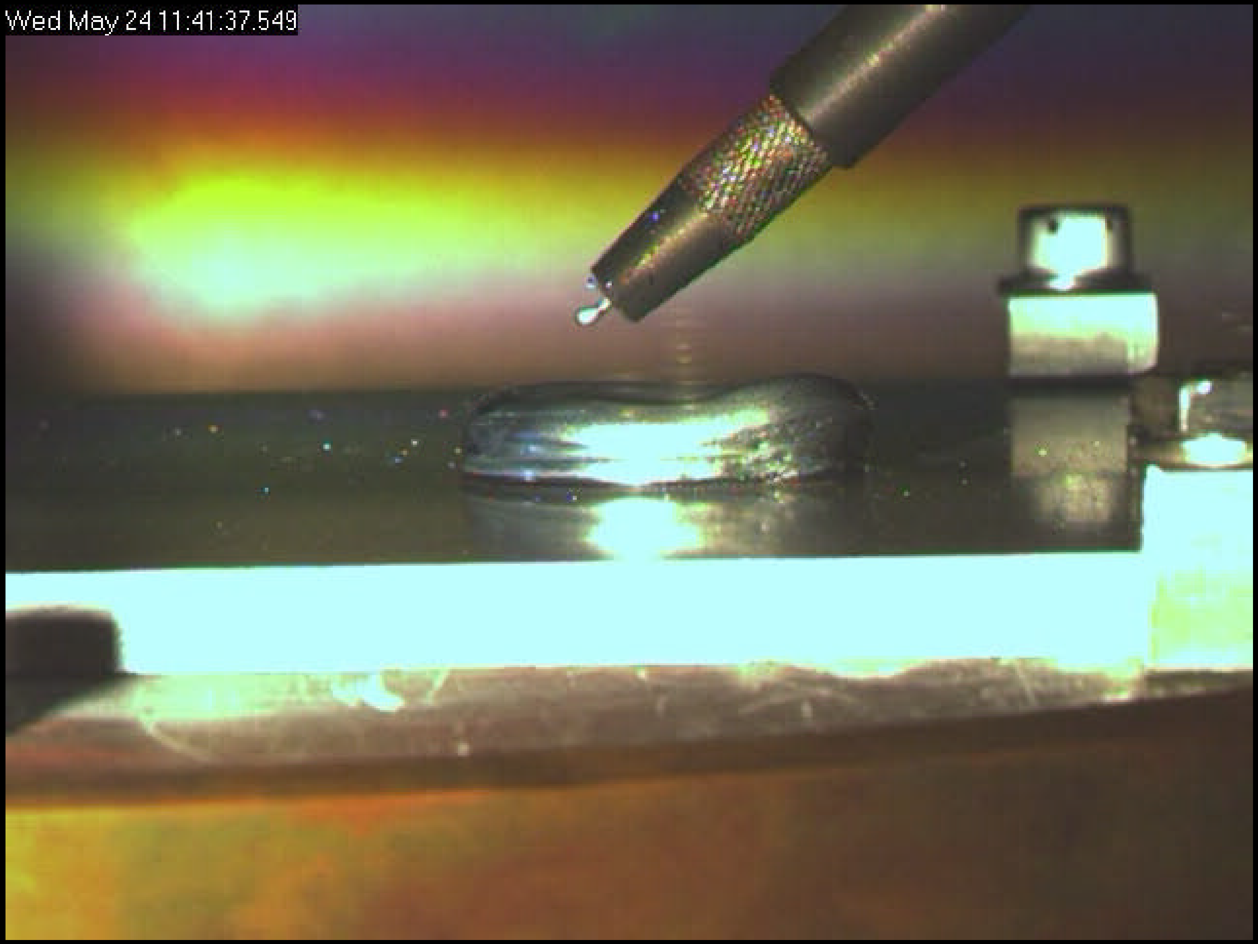
Successful Demonstration of EBF³ in 0-g

Circle, Layers 7 & 8



- **Process able to heal surface irregularity from initial ball**
- **Process works well if correct distance maintained**

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Conclusions

- Successfully demonstrated EBF^3 deposition of 2219 Al in 0-g over range of processing conditions
  - translation speeds
  - wire feed rates
  - wire entrance angle with respect to translation direction
- Initial demonstrations showed deposit geometry is dominated by surface tension in 0-g and 1-g
  - very little difference in height and width between 0-g and 1-g
- Identified distance between wire tip and substrate and thermal input as critical variables to control
  - when correct, process operates well and heals surface irregularities

Future Plans

- **Last week of microgravity flights (Sept. 2007)**
  - **Welding trials**
  - **Height sensitivity tests**
  - **Closed loop control demo**
  - **Solid block**
  - **Repair strategies**

- **2nd and 3rd generation portable systems under development**
  - **Move towards space flight configuration**
  - **Reduce mass, size**
  - **Moveable gun inside vacuum chamber**
  - **Different positioning system configurations**
  - **Potential integration of machining and NDE functions**

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