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Comparison of LCAC and PM Mo deposited using Sciaky EBAM™

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A B S T R A C T

A Sciaky electron beam additive manufacturing (EBAM™) system was used to deposit low-carbon arc-cast (LCAC) and powder metallurgy (PM) Mo onto corresponding substrates. Results show dramatic differences in the quality of the two deposited materials. LCAC deposits were crack-free with low porosity while the PM material contained gross porosity and cracks. Analytical data highlighted that the difference in deposition behavior can be attributed to differences in the concentration of volatile elements such as Ca, Na and low boiling point oxides present in the starting materials.

1. Introduction

Wire feed additive manufacturing technology such as the EBAM system developed by Sciaky are of interest for a variety of applications. The EBAM system is capable of depositing relatively large volumes of metal in a short amount of time. High density desposits require suitable materials and parameters. The Sciaky technique essentially utilizes an electron beam welding machine to deposit material in layers. By building up layers of weld beads, vertical walls or other structures can be built. A schematic of the process is shown in Fig. 1 [1].

2. Experimental procedure

Low-carbon arc-cast (LCAC) and powder metallurgy (PM) bars were swaged and drawn down to 1.57 mm OD wire per ASTM B387 Types 365 and 361, respectively. LCAC and PM plates were rolled to 12.7 mm thickness per ASTM B386 Types 365 and 361, respectively. Chemistry of all materials were tested via GDMS and IGA (LECO) methodology. Arc-cast wire was deposited onto arc-cast substrates; powder metallurgy wire was deposited onto powder metallurgy substrates.

Initial trials depositing LCAC with a Sciaky EBAM 300 system were unstable in continuous electron beam operation mode. The resulting unstable melt pools yielded inconsistent surface finish and deposition rates. Better results were achieved in pulsed e-beam mode. The optimized parameters for this evaluation were listed in Table 1.

The goal of this evaluation was the build of straight wall deposits and square trays from LCAC and PM Mo wire with target tray dimensions of 100 mm × 100 mm × 50 mm tall with a wall thickness of 3.2 mm. After the build, samples of each build material were sectioned and analyzed for density, microstructure and chemistry. GDMS and IGA analysis were repeated after the build.

A machining trial was performed on an LCAC Mo tray to verify the machinability of the deposited material. Walls were milled on both sides from a starting thickness of 3.2 mm down to a finished thickness of 2 mm.

3. Results and discussion

Fig. 2 shows the initial deposition trials using continuous electron beam power. The weld beads were unstable and prone to bulging due to molten Mo surface tension. To control this instability, operation was switched to pulsed electron beam power. The improved deposition consistency is shown in Fig. 3.

Square tray builds were attempted after establishing the basic build parameters on straight walls. Fig. 4 shows the successful build of a tray using the LCAC feed wire. Overall the LCAC Mo metal deposited consistently without major porosity or cracking, but some minor geometric defects did occur Additional development work is required for resolving issues with corner geometry and the wire feed deviating from the desired position on the wall.

Powder metallurgy (PM) Mo feed-wire builds were more difficult than the LCAC wire builds. Fig. 5 shows a tray built from PM wire using identical build parameters as the LCAC material. There was significant porosity and cracking observed in the deposited material.

During the PM deposition process, dramatic sparks/expulsion of material were observed coming from the melt pool. Additionally, a significant amount of spatter built up on the PM Mo substrate compared to LCAC Mo substrate. A camera in the Sciaky system monitored the melt pool as shown in Figs. 6 and 7. The LCAC Mo melt pool in Fig. 6 is smooth & uniform while the PM Mo melt pool in Fig. 7 shows the formation of blisters/pores and visible sparks/expulsions indicating that volatile materials are being released during the melting process.

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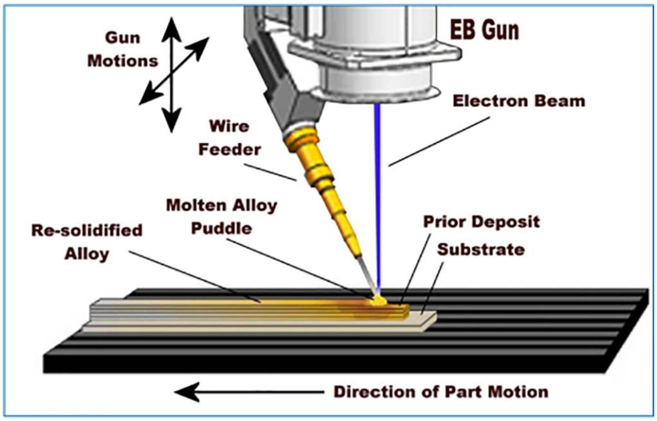

Fig. 1. Schematic of the Sciaky EBAM process [1].

Table 1
Sciaky build parameters for Mo.

Wire feed speed	76 cm/min
Average power	35 kV at 110 mA
Surface travel speed	25 cm/min
Deposition rate	0.91 kg/h

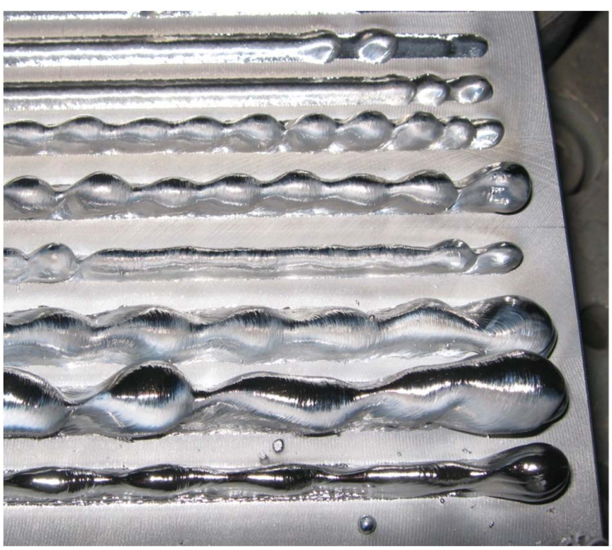

Fig. 2. Initial LCAC deposits made using continuous e-beam power that resulted in inconsistent weld bead behavior.

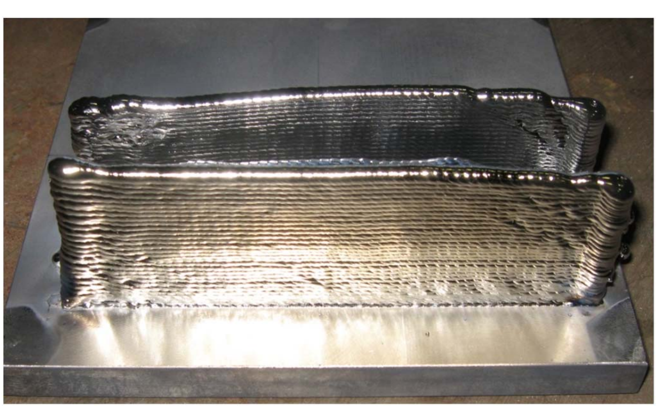

Fig. 3. Optimized LCAC deposits made using pulsed e-beam power.

Sections of the deposits were analyzed for density and microstructure. For the LCAC material, density was measured at the top and middle of the wall heights. For the PM material, density was measured at the top, middle and bottom of a wall section. Density values were recorded in Table 2. Density of the LCAC material (99+ %) was much higher than the PM material (95–96%).

The Sciaky process involves melting. Consequently, the microstructure was quite coarse with columnar grains spanning the height of the build in the LCAC Mo as shown in Fig. 8.

Optical microscopy of the LCAC Mo is shown in Fig. 9. The transverse microstructure of the LCAC material near the location where the wall meets the baseplate shows a transition from the fine grains of the baseplate to the large, melted, columnar grains of the wall deposit.

Fig. 10 shows the transverse microstructure of the powder metallurgy material. The numerous large voids that exist correlate to the voids seen in the melt pool photos of Fig. 7. The grains of the powder metallurgy material are slightly smaller than the LCAC material. The voids may impact grain growth during the build in the PM material.

Chemistry of the starting materials and the deposits were evaluated by GDMS and IGA chemical analysis. Complete tabulated results of the chemical analysis were recorded in Appendix A. Chemistry appears to be a root cause for the expulsions and voids in the PM Mo compared to the LCAC Mo. Fig. 11 is a bar chart of the detected chemical elements with a boiling point less than Mo at 1 atm. The Sciaky melted deposits have significantly lower impurity levels than the starting wire.

The starting PM Mo wire has over 100 ppm of lower boiling point elements compare to < 25 ppm for the LCAC material. The larger starting concentration of the these elements in the PM wire is most likely a key contributor to the porosity and expulsions seen during the deposition of this material.

Fig. 12 plots the impurity change from the starting wire and the Sciaky deposit for each element. The largest reductions for the powder metallurgy material are for O, Ca, Na and Sb. These are the leading suspects for causing the porosity and expulsions during the deposition process.

The Sciaky EBAM process is essentially a welding process. Previous experimental efforts on welding of molybdenum have shown a recommended preference for low carbon arc-cast material over powder metallurgy material [2–4]. Bryhan, in his experimental procedures for welding of molybdenum, suggested that powder metallurgy weldments will contain gas porosity and recommended using arc-cast materials to avoid such defects [2]. Similar observations were reported by earlier researchers [3,4]. By using a melting technique as part of the manufacturing process, LCAC molybdenum does not contain the volatile, gas forming impurities left behind at typical powder metallurgy sintering temperatures. The resultant chemical refining of the LCAC material leads to reduced defects in the EBAM deposits.

Machining trials were performed on both the powder metallurgy and LCAC deposits. The PM build material was brittle and contained numerous cracks and proved impossible to machine compared to the LCAC Mo build. Milling of the entire wall height of the LCAC tray as shown in Fig. 13 was conducted with minor issues. The large columnar grains were more visible after milling. One crack was observed along a columnar grain. This is not considered unusual since coarse-grained, as-cast Mo is typically quite brittle and will fail along grain boundaries.

4. Conclusions

- Arc-cast Mo material can be successfully deposited using the Sciaky process.
- Powder metallurgy wire was not successfully deposited. The material had voids, cracking and significant expulsions during the process that resulted in poor quality deposits.
- The expulsions occurring during the PM deposits were the result of volatile elements being vaporized. Chemical analysis highlighted O, Ca, Na and Sb as likely candidates in causing the expulsions.