Elucidating the Effect of Additive Friction Stir Deposition on the Resulting Microstructure and Mechanical Properties of Magnesium Alloy WE43

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Abstract: In this work, the effect of processing parameters on the resulting microstructure and mechanical properties of magnesium alloy WE43 processed via Additive Friction Stir Deposition (AFSD), a nascent solid-state additive manufacturing (AM) process, is investigated. In particular, a parameterization study was carried out, using multiple four-layer deposits, to identify a suitable process window for a structural 68-layers bulk WE43 deposition. The parametric study identified an acceptable set of parameters with minimal surface defects and excellent consolidation for the fabrication of a bulk WE43 deposition. Microstructural, tensile, and fatigue life characterization was conducted on the bulk WE43 deposition and compared to commercially available wrought material to elucidate the process-structure-property-performance (PSPP) relationship of the AFSD process. This study shows that the bulk WE43 deposit exhibited a refined homogenous microstructure and a texture shift relative to the wrought material. However, a reduction in hardness and tensile behavior was observed in the as-deposited WE43 compared to the wrought control. Additionally, fatigue specimens extracted from the bulk deposition exhibited a decrease in life in the low-cycle regime but performed comparably to the wrought plate in the high-cycle regime. The outcomes of this study illustrate the potential of the AFSD process in additively manufactured structural load-bearing components made with magnesium alloy WE43 in the as-built condition.

Keywords: solid-state additive manufacturing; additive friction stir deposition; magnesium alloy WE43; texture analysis; fatigue behavior

1. Introduction

Due to the increasing demand for high strength and low-density alloys in the automotive, aerospace, and biomedical industries, the use of magnesium alloys has become more prevalent [1–3]. Magnesium alloys are one of the lightest structural metals, possessing a density of 1.7 g/cm3. In traditional manufacturing methods of magnesium alloys, several issues arise, including hot cracking, porosity, and limited cold working ability, in addition to high costs, which has limited the development and usability of these alloys [4–7]. To combat these issues, there has recently been a push for the rapid manufacturing of magnesium alloys using various additive techniques.

Additive manufacturing (AM) is a rapid manufacturing process in which materials are deposited layer-by-layer to create complex 3D components from model data [8]. AM processes have the ability to increase manufacturing efficiency through decreases in product development time, material waste, and costs [9]. Beam-based and limited solid-state techniques such as selective laser melting (SLM), wire arc additive manufacturing (WAAM),
laser powder bed fusion (LPBF), and additive friction stir layer welding (AFSLW) have been reported to manufacture magnesium alloys additively. The components produced via SLM experienced increased temperature gradients, resulting in hot cracking, rapid grain growth, and localized stress concentrations [10,11]. As a result, the SLM build had a decrease in mechanical performance when compared to the wrought magnesium alloy [10,11] WAAM produced builds experienced a more refined microstructure and an increase in creep performance; however, the builds exhibited some porosity and a decrease in mechanical performance when compared to the wrought magnesium alloy [12,13]. The LPBF process created a 99% dense build with minor porosity and defects with a refined microstructure; however, a significant decrease in mechanical performance compared to wrought material was reported [14]. The AFSLW method that uses a pin tool to join layers of the material through thermomechanical processing produced a fully dense build with a refined microstructure. However, the AFSLW builds reported a decrease in hardness, monotonic, and fatigue performance when compared to the wrought magnesium alloy [15,16]. Materials classified as unweldable and difficult to additively manufacture using beam-based methods are able to be manufactured using the AFSD process since no melting and re-solidification occurs, eliminating common issues in beam-based additive manufacturing such as hot-cracking and porosity.

Additive Friction Stir-Deposition (AFSD) is a nascent solid-state AM method derived from the ideologies of friction stir welding (FSW) and the friction stir cladding technique developed by Stelt et al. [17]. The AFSD process is a thermomechanical deposition process, as shown in Figure 1, that utilizes a non-consumable, hollow, rotating tool that deposits feedstock material layer-by-layer. Researchers have noted that the severe plastic deformation induced by the hollow tool shoulder and deposited layer instigates dynamic recrystallization (DRX), generating a refined microstructure in the materials [16,18–20]. The deformed material is shaped by the tools path layer-by-layer until the desired component dimensions have been achieved. Each consecutive layer is re-stirred and metallurgically bonded to the previous layer due to the tool geometry described in Avery et al. [21] and Robinson et al. [22]. The AFSD process has the ability to produce a fully dense build with a refined and homogenous microstructure and exhibit wrought-like mechanical properties in materials such as structural and high-strength aluminum alloys [19–21,23–33], magnesium alloys [22], and Inconel alloys [18,34].

![Figure 1](image-url)
In this present work, the development of an acceptable process parameter window for AFSD of magnesium alloy WE43 is identified for the first time. Furthermore, in-depth characterization of the resulting microstructure and mechanical properties, including quasi-static and fatigue tests, are conducted. The results of this study illustrate the potential of using AFSD to fabricate bulk structural components in magnesium alloy WE43 additively.

2. Materials and Methods

2.1. Materials and AFSD Process Parameter Development

All solid-state depositions used in this study were created using a commercially available B8 machine (MELD Manufacturing, Christiansburg, VA, USA). A general schematic of the AFSD process and parameter development tool path are detailed in Figure 1a. For the initial parameter study, the tool path traverses 50.8 mm along the longitudinal direction (LD) to deposit odd layers represented in white. Then, the head raises 1 mm and begins to move 50.8 mm in the opposite direction of the previous layer along the LD axis to deposit even layers represented in red. An experimental study was performed to identify the appropriate process parameters for WE43. Similar AFSD parameters for Mg Alloy AZ31 reported by Robinson et al. were used as an initial baseline for the parametric study [22]. The parametric study varying spindle speed ($\omega$), actuator feed rate (F), and traversing velocity (V) was performed until a well-consolidated build with no surface defects was obtained. It should be noted that the parameter study samples will be referred to as Build X, where X is a number 1–28, which correlates to the specific parameters. The hollow AFSD tool used in this study, as dimensioned in Robinson et al. [22], is made of H13 tool steel that includes four offset “teardrop” features on the tool shoulder. These features increase the frictional heat and stir previously deposited layers, inducing high shear and severe plastic deformation of the deposited material to metallurgically bond the deposited layers [29]. Figure 1b depicts a schematic of the AFSD stir zone created by the “teardrop” features and the resulting interaction with previously deposited layers. All WE43 used in this study had the nominal composition given in Table 1. The WE43-T5 feedstock material used for these builds was a 9.53 mm by 9.53 mm rod with a length of 305 mm machined from a rolled plate. The feedstock rods were coated in a spray graphite lubricant, per recommendation from the manufacturer, to prevent jamming of the WE43-T5 feedstock rods within the hollow tool. The process parameter depositions were made on a respective WE43-T5 substrate plate, measuring 76.2 mm in width, 153 mm in length, and 6.35 mm in thickness.

Table 1. Chemical composition (in wt.%) of magnesium alloy WE43, data from [35].

|        | Mg | Li | Mn | Nd  | Y   | Zn | Zr  | RE  |
|--------|----|----|----|-----|-----|----|-----|-----|
| Bal.   | 0.05 | 0.03 | 2–2.5 | 3.7–4.3 | 0.06 | 0.2–1 | 0.3–1 |

After the parameter study has been completed, one parameter set was chosen to create a large deposition, which for clarity is referred to as the bulk WE43 deposition, to machine tensile and fatigue specimens from both the build direction and longitudinal direction, as shown in Figure 2a. The parameters included a spindle speed of 325 RPM, an actuator feed rate of 63.5 mm/min, and a traverse velocity of 152.4 mm/min. The bulk WE43 deposition was made on a WE43-T5 plate, measuring 76.2 mm in width, 254 mm in length, and 6.35 mm in thickness. The deposition length, width, and height were 157 mm, 38.1 mm, and 68.6 mm, respectively. Figure 2b shows an isometric view of the completed bulk WE43 deposition and the relative location, denoted by the red dashed lines, of the micrograph in Figure 5b.
Table 1. Chemical composition (in wt.%) of magnesium alloy WE43, data from [35].

| Element | Composition (%) |
|---------|----------------|
| Mg      | Bal.           |
| Li      | 0.05           |
| Mn      | 0.03           |
| Nd      | 2–2.5          |
| Y       | 3.7–4.3        |
| Zn      | 0.06           |
| Zr      | 0.2–1          |
| RE      | 0.3–1          |

Figure 2. Schematics illustrating (a) locations of specimens machined in the longitudinal (LD) and build (BD) directions for the bulk WE43 deposition, (b) a macroscopic image of the bulk WE43 deposition after completion, and (c) dimensions of the specimens used in this study.

2.2. Microstructure Characterization

The WE43-T5 feedstock and all AFSD WE43 specimens were cold mounted in EpoxiCure 2 epoxy resin for microstructure characterization. The mounted specimens were stepwise ground and polished to 1 µm using an oil-based diamond suspension with a final polish using a 0.05 µm aluminum oxide solution. Electron backscatter diffraction (EBSD) on the specimens was performed on an Apreo FE-SEM equipped with an EDAX Hikari Super EBSD camera (EDAX, Mahwah, NJ, USA) with a voltage, current, and step size of 20 kV, 6.4 nA, and 0.4 µm, respectively. Post-processing analysis of the EBSD scans was completed using the EDAX TEAM software (Team, EDAX, Mahwah, NJ, USA) in compliance with ASTM 2627-13 [36]. All fracture surfaces were examined on the Apreo FE-SEM (ThermoFisher Scientific, Waltham, MA, USA). Hardness measurements were obtained using a Wilson VH1202 microhardness tester (Buehler, Lake Bluff, IL, USA), abiding by ASTM E384-16 [37], with a load of 500 gf and a 15 s dwell time. The measurements were taken in 2 rows, separated by 1 mm, down the middle of the deposition from the top to the bottom of the bulk WE43 deposit.

2.3. Bulk WE43 Deposition Quasi-Static Tensile Response

Quasi-static tensile testing was performed in triplicate on the WE43-T5 feedstock in both the build and longitudinal directions of the bulk WE43 deposit, as shown in Figure 2a. Figure 2c indicates the modified ATSM E606/E606M-12 [38] dimensions of the specimens used for both the monotonic and fatigue experiments for both orientations. The specimens were tested at ambient laboratory conditions using a 25 kN Landmark 370 MTS servohydraulic load frame (MTS, Eden Prairie, MN, USA). The tests were run in displacement control with a 5 mm gauge extensometer at a nominal strain rate of 0.001 s⁻¹. Specimens prepared from the WE43-T5 feedstock were tested in the same conditions for comparison. All the builds depicted in Figure 2a were machined with a Mitsubishi MV1200 wire electron discharge machine (EDM) (Mitsubishi Corporation, Tokyo, Japan) to the specified dimensions.
2.4. Bulk WE43 Deposition Fatigue Behavior

The fatigue geometry for the load-controlled tests was the same as the monotonic tests and was machined with a Mitsubishi MV1200 wire EDM (Mitsubishi Corporation, Tokyo, Japan) before being hand polished to 1200p, roughly 600 grit, to eliminate surface defects and recast layers that may cause early crack initiation and failure. The fully reversed (R = −1) tests were performed on a servohydraulic MTS Landmark 25 kN load frame at 20 Hz with a sine wave loading profile. The specimens were gripped using MTS flat grips and tested in a load controlled with a PVC tuner to control the PID after manual tuning to eliminate the potential for work hardening due to overshoot. The builds were tested at three stress levels, 207, 172, and 138 MPa, with the maximum stress found by measuring the cross-sectional area of the individual specimen to calculate the required load to reach the desired applied stress. Three specimens at each stress amplitude were tested in the BD and LD that were compared to three specimens prepared from WE43-T5 feedstock for comparison.

3. Results and Discussion
3.1. AFSD Process Parameter Development and Characterization

A 28-parameter set DOE probed the influence of the individual process parameters on the resulting deposited material. The tabulated version of all 28 WE43 process parameters, including corresponding as-deposited build hardness values where applicable, as probed in this study, is located in the Appendix A (Table A1). The different parameters describe a process that depends heavily on the three most influential parameters in AFSD: F, ω, and V. It is concluded that a lower ω and F are more favorable when depositing WE43 and that the builds with a higher deposition ratio (V/F) resulted in a more favorable deposition. From these graphs, there is evidence to suggest that WE43 depositions have a narrow thermal input window, and any parameter that does not fall within the bounds of this window would cause one or multiple macroscopic defects such as galling, poor material bonding, or excess flash, as shown in Figure 3.

Figure 3. Representative morphologies of the WE43 AFSD material during process optimization study of deposits with (a) no macro defects and well-consolidated build, (b) minor macro defects and well-consolidated build, (c) significant defects, (d,g) optical microscopic image of Figure 3a’s cross-section, (e,h) optical microscopic image of Figure 3b’s cross-section, (f) and (i) optical microscopic image of Figure 3c’s cross-section.
Representative images of WE43 builds with a ranging severity of defects are shown below in Figure 3a–c respectively, while Table 2 details the parameters implemented for each of the WE43 builds described in Figure 3. Figure 3d–f show micrographs including the cross-sections of the respective WE43 builds that were sectioned along the middle of the build to ensure a fully dense deposit was achieved, while Figure 3g–i are zoomed-in micrographs of areas of interest within each build. It should be noted that the horizontal dashed lines in Figure 3d–f define the boundary between the substrate and the deposit. Build 8 exhibited no macroscopic defects and is considered a fully dense build, portraying fully bonded layers. Figure 3d shows a significant amount of material mixing of the feedstock deposition material and substrate, which is caused by the features on the tool stirring previous layers and helping with the metallurgical bonding between the substrate and the deposit. Build 10 illustrates minor surface defects such as flash and galling, as shown in Figure 3b, but the cross-section of Build 10 is fully dense and has a similar substrate deposit interface interaction as discussed with Build 8. The minor surface defects in Build 10 are likely caused by insufficient material feed rate and heat generation within the consecutive layers of the build. Build 12 has major macroscopic defects, as shown in Figure 3c, while Figure 3f,i show that there is minimal layer bonding, suggesting that there is not enough thermal input into the build to keep the material flowing correctly. It should also be noted that Build 12 lacks material mixing between the substrate and the deposit, causing poor layer bonding between successive layers.

| Build Number | ω (RPM) | F (mm/min) | V (mm/min) | Deposition Ratio (V/F) | Macro Defects | Hardness (HV) |
|--------------|---------|------------|------------|------------------------|---------------|---------------|
| 8            | 325     | 63.5       | 152.4      | 2.40                   | None          | 82.0          |
| 10           | 350     | 50.8       | 101.6      | 2.00                   | Galling       | 80.3          |
| 12           | 350     | 101.6      | 101.6      | 1.00                   | No Bonding    | X             |

While not all builds are shown for brevity’s sake, cross-sectioned images of all 28 parameters, similar to those shown in Figure 3d–f, revealed that WE43 has a relatively large processing window compared to other AFSD magnesium alloys [22]. Many of the WE43 parameter builds revealed minor macroscopic defects on the surface and galling but were still well consolidated throughout the cross-section. Only taking macroscopic defects into account, the specific parameter set proposed for the bulk WE43 deposition was the one used for Build 8 (see Table 2), which lacked macro defects such as flash and galling and was fully dense. Table A1 also shows that all the well-consolidated builds had a similar average Vickers hardness ranging from 76 to 84 HV with minimal scatter in the data. The slight discrepancies in hardness between process parameter builds suggest differentiating thermal inputs and severe plastic deformation experienced during each parameter set. It should be noted that all the build’s hardness values were lower than the average WE43-T5 feedstock hardness value of 101 Hv. Since the hardness of these builds was relatively consistent, the macroscopic evaluation was deemed a more important factor in selecting the process parameters.

For added process parameter comparison, the as-deposited WE43 microstructure from Build 8 was compared to the WE43-T5 feedstock in Figure 4. The EBSD images of the grain morphologies and inverse pole figure (IPF) orientation for the feedstock and deposited material are depicted in Figure 4a,b, respectively. Figure 4d represents the relative EBSD location within the cross-section of Build 8, while Figure 4c plots the comparison of the calculated grain size diameter for the feedstock and deposition. The average grain sizes for the WE43-T5 feedstock and the WE43 AFSD Build 8 are 45 and 2.7 microns, respectively.
Metals 2021, 11, x FOR PEER REVIEW 7 of 19

deposited material are depicted in Figure 4a,b, respectively. Figure 4d represents the rel-
ative EBSD location within the cross-section of Build 8, while Figure 4c plots the compar-
ison of the calculated grain size diameter for the feedstock and deposition. The average
grain sizes for the WE43-T5 feedstock and the WE43 AFSD Build 8 are 45 and 2.7 microns,
respectively.

Figure 4. Representative EBSD of (a) WE43-T5 feedstock and (b) WE43 AFSD Build 8. (c) Representative grain size of the
WE43-T5 feedstock and AFSD Build 8, (d) location of EBSD scans within Build 8.

The WE43-T5 feedstock material in Figure 4a suggests a strong basal plane <0001> tex-
ture orientation and inhomogeneous grain morphology, while the IPF for the as-deposited
WE43 in Figure 4b suggests a more random texture and homogenous grain morphology.
Comparing the grain size diameter in Figure 4c for the WE43-T5 feedstock and as-deposited
material results in a significantly reduced grain size diameter band after deposition from
the coarser-grained feedstock. This refined microstructure stems from the DRX caused by
the tool’s severe plastic deformation of the material.

3.2. Microstructural Characterization for Bulk WE43 Deposit

The micrograph in Figure 5b depicts a sectioned view of the bulk WE43 deposition
build direction, which consisted of 68 layers, had minimal surface defects, and is well
consolidated and defect-free. The approximate location of the micrograph in Figure 5b
correlates to Section AA in the bulk WE43 deposition shown in Figure 2b. The dark and
light bands in Figure 5b suggest oxide layer boundaries, as described by Phillips et al. [25],
which are caused by the alternating tool path depicted in Figure 1a.

A hardness map portraying data from the top to the bottom of the build direction and
EBSD maps and the corresponding calculated grain size is shown in Figure 5. Figure 5a
presents the results of the Vickers microhardness tests that were completed on a cross-
section in the build direction of the bulk WE43 deposition. The location of the hardness
indents correlates to the approximate position in the build direction on the micrograph in
Figure 5b. The average hardness throughout the depositions entire height was 81 ± 3.8 HV;
however, it should be noted the hardness data in Figure 5a show that the top and immediate
bottom of the deposition have a higher hardness than the middle section of the deposition. The slight decrease in hardness throughout the bulk WE43 deposition likely originates from the irregular thermal cycles and severe plastic deformation experienced during the AFSD process. As the number of thermal cycles increases, the layers closer to the bottom of the deposition are subjected to an elevated temperature for a more extended period of time, suggesting that the strengthening precipitates in the matrix are slightly more coarsened when compared to those near the top of the deposition. This coarsening of strengthening precipitates has been recorded in studies by Palanivel et al. [15] on magnesium alloy WE43 and Mason et al. [29] on 7xxx series aluminum alloys. The layers near the immediate bottom of the deposition interact and get mixed with the WE43-T5 substrate from the tool shoulder protrusions, as shown in Figure 3g, which likely results in higher hardness values and a large scatter band in these bottom layers. However, the overall hardness throughout the bulk WE43 deposition is relatively consistent, ranging from 79 to 89 HV, which implies that minimal coarsening of the strengthening precipitates occurred.

Figure 5c–e represent the EBSD scans and average grain size of the top, middle, and bottom of the bulk WE43 deposition, respectively. The locations of these scans are indicated by the box around the corresponding hardness value location. The average grain sizes throughout the top, middle, and bottom possess a homogenous grain morphology with relatively consistent grain sizes at 4.8 µm, 3.5 µm, and 4.5 µm, respectively. The average grain size of WE43-T5 feedstock is 45 µm, as shown in Figure 4a, and it has an inhomogeneous grain morphology consistent with the WE43-T5 plate found in the literature [39–41]. There is a 90% grain size reduction from the feedstock to the bulk WE43 deposit, which correlates with previous AFSD studies [20,23,34]. The grain size reduction and shift in grain morphology in the bulk WE43 deposition are caused by a large amount of plastic deformation and DRX experienced during the AFSD process. It should be noted that the successive layers increased the number of heat cycles experienced by the build,
which caused the bulk deposition’s grains to coarsen slightly, resulting in larger grain size than in Build 8 from the parameter study. However, there should not be a concern of decreased performance when compared to Build 8, since the coarsening of the grains was consistent throughout the entire deposition.

Figure 6a–d illustrate the representative texture plots of the WE43-T5 feedstock, top, middle, and bottom regions of the bulk WE43 deposition, respectively. In the areas analyzed, the basal plane <0001> had the strongest texture intensity, which is common among magnesium alloys [42–44]. In the <1010> and <1120> plane, the texture switches from a more randomized texture with moderate intensity in the feedstock to a banded texture with low intensity in the bulk WE43 deposit, which is likely due to the severe plastic deformation and mechanical stirring induced by the tool geometry during the AFSD process. This low-intensity banding texture within the deposit is similar to the nugget zone of friction stir processed WE43 [15–45]. Within the basal plane, there is a decrease in texture intensity from the feedstock to the top and middle of the bulk WE43 deposit. A recent study by Kumar et al. observed a similar trend of low texture intensity in friction stir processed magnesium alloys containing rare earth elements such as WE43 [39]. It should be noted that in the bottom of the bulk WE43 deposition, the texture intensity is slightly higher than the WE43-T5 feedstock. This is likely because of the inherent mixing of the substrate and deposition in the initial layers of the build due to the AFSD process and tool geometry, as discussed previously. Overall, the texture intensity is significantly lower than other magnesium alloys, such as AZ31 [22], which was manufactured via AFSD. The lower texture intensity is attributed to the addition of rare earth alloying elements within WE43 [46].

| (a) Feedstock | 0 0 0 1 | 0 0 0 1 | 0 0 0 1 |
|---------------|---------|---------|---------|
| (b) Top       | 0 0 0 1 | 0 0 0 1 | 0 0 0 1 |
| (c) Middle    | 0 0 0 1 | 0 0 0 1 | 0 0 0 1 |
| (d) Bottom    | 0 0 0 1 | 0 0 0 1 | 0 0 0 1 |

Figure 6. Representative texture plots for the (a) WE43-T5 feedstock material, (b) top of the deposition, (c) middle of the deposition, and (d) bottom of the deposition.
3.3. Quasi-Static Response of Bulk WE43 Deposit

Figure 7 shows the tensile results of the longitudinal (LD) and build (BD) directions of the bulk WE43 deposition compared to the WE43-T5 feedstock and WE43 as-cast [47] material. All builds had a consistent modulus of elasticity at 44 GPa. Overall, the bulk WE43 deposit had a decrease in strength when compared to the WE43-T5 feedstock but had an increase in strength compared to the WE43 as-cast material. Table 3 exhibits a detailed comparison of the yield strength (YS), ultimate strength (UTS), and failure strain for the LD and BD for the bulk WE43 deposition, the WE43-T5 feedstock, the WE43 as-cast, and WE43 LPBF tensile behaviors. The LD experienced a 30.7% and 29.4% reduction in yield strength and UTS, respectively, from the WE43-T5 feedstock material. However, the ductility of the LD increased by 40% compared to the WE43-T5 feedstock material. The as-deposited BD experienced similar mechanical reductions in the YS and UTS at 35.5% and 45.4%, respectively, from the WE43-T5 feedstock material. However, unlike in the LD, the ductility of the BD decreased by 54.3% compared to the WE43-T5 feedstock material. The decreased mechanical response in the BD is likely due to oxidation and carbides from the graphite coatings on the feedstock rods becoming entrapped in layer interfaces [25], causing slight anisotropy in the bulk WE43 deposit. The observed anisotropy is similar to that reported in magnesium alloys created by beam-based AM methods [48]. Although the LD and BD do not perform as well as the WE43-T5 feedstock, the YS and UTS have a minimum increase of 41.6% and 3.5%, respectively, when compared to the WE43 as-cast material. The LD and BD have superior mechanical performance compared to the WE43 as-cast material because of the large amounts of severe plastic deformation and DRX induced by the heat input and mechanical stirring of previous layers inherent to the AFSD tooling used in this study. The LD has a 4.8% decrease in YS when compared to the WE43 LPBF process; however, the LD UTS has a 5.4% increase compared to the WE43 LPBF. The WE43 LPBF reported a significant reduction in failure strain when compared to the LD, BD, and as-cast samples. However, increased thermal cycles expose previous layers during AFSD, encouraging the coarsening of strengthening precipitates, as discussed previously, which is likely the cause for the decreased mechanical performance of bulk WE43 deposit when compared to the WE43-T5 feedstock. Future research should investigate a deposition made in an inert atmosphere to mitigate oxidation effects and the strength regained when a T5 temper is applied to an as-deposited WE43 build.

![Figure 7. Stress-strain plot comparing the quasi-static tensile test results of the WE43-T5 feedstock, longitudinal direction, and build direction of the bulk WE43 deposition.](image-url)
3.4. Fatigue Behavior for Bulk WE43 Deposition Specimens

The results of the stress-controlled fatigue tests are presented below in Figure 8 for the WE43-T5 feedstock, LD, and BD for the bulk WE43 deposition. At the lower stress levels in Figure 8a, the bulk WE43 deposit samples in both directions show a closer comparison to the feedstock, with the LD out-performing a feedstock build at 138 MPa, but at 207 MPa, the BD samples suffered failure within a hundred cycles. This reduction in life can be captured by normalizing the applied stress amplitude to the specimens UTS, where it is seen in Figure 8b that this results in a linear relationship between all three specimen cases. The strong relationship between the normalized stress elucidates the reason for the reduction in life, especially for the BD as it was being tested at over 90% of its UTS while the WE43-T5 feedstock was being tested below 60% of its own UTS. This trend in life and UTS suggests that the same layer defects reducing the monotonic properties of the BD are the same mechanisms controlling the reduction in life to failure and that optimizations of the process and implementations of heat treatment that improve the monotonic properties will offer a similar increase to the fatigue life.

At the lowest stress level, the applied loads are below yield for all specimens; therefore, there is no large-scale plastic deformation that the BD cannot accommodate due to its limited elongation to failure. So, while the bulk WE43 deposit specimens still have interlayer defects intrinsic from the manufacturing process that act as stress concentrations, their effect is shown to be reduced, as seen by the fatigue life of the LD and the WE43-T5 feedstock overlapping at the lowest stress amplitude. The results in Figure 8 show that the LD has superior fatigue performance when compared to the BD results, but the AFSD results still depict a reduction in life when compared to the WE43-T5 feedstock fatigue behavior.

![Figure 8](image-url)  
**Figure 8.** (a) S-N plot and the (b) S-N plot normalized by UTS for load-controlled fatigue testing of the bulk WE43 deposition build direction, longitudinal direction, and WE43 T-5 feedstock builds at three stress levels.

### Table 3. The YS, UTS, and FS for various WE43 specimens.

| Sample                  | Yield Strength (MPa) | Ultimate Strength (MPa) | Failure Strain (%) |
|-------------------------|----------------------|-------------------------|--------------------|
| WE43-T5 Feedstock       | 278 ± 2.4            | 355 ± 2.4               | 11.7 ± 1.5         |
| WE43 AFSD LD            | 204 ± 8.0            | 264 ± 0.87              | 17.4 ± 0.22        |
| WE43 AFSD BD            | 194 ± 8.8            | 224 ± 9.7               | 6.7 ± 1.3          |
| WE43 As Cast [48]       | 137                  | 217                     | 8.2                |
| WE43 LPBF [14]          | 214.4 ± 3.54         | 250.9 ± 2.92            | 2.62 ± 0.29 *      |

*—ASTM E8M-3856.
3.5. Fractography for Bulk WE43 Deposition Specimens

The failed quasi-static and fatigue samples were examined under optical microscopy and electron microscopy to evaluate the fracture surfaces and failure mechanisms in an attempt to understand the difference between the material properties seen in the bulk WE43 deposit when compared to the WE43-T5 feedstock. Figures 9 and 10 show the fracture surfaces from quasi-static and fatigue testing, respectively.

![Fractography images](image)

**Figure 9.** Low magnification optical microscopy of representative quasi-static fractured samples from the WE43-T5 feedstock. LD and BD of the bulk WE43 deposition. Higher magnification electron microscopy shows signs of ductile failure present in all three builds though AFSD shows flat regions that resemble brittle fracture.

For the quasi-static tensile specimens reported in Figure 9, it was seen in the fractography in Figure 10 that the LD and BD specimens showed flat regions of failure perpendicular to loading that is not seen when examining the WE43-T5 feedstock. Higher magnification imaging of these regions showed microvoid formation as well as failure along certain metallographic planes that can be seen as well in the feedstock images. The mixed-mode of microvoid growth with fracture along certain planes is common in WE43, and similar Mg alloys in monotonic and fast fracture regions as certain grains are oriented to prefer fracture along their basal planes [49–51]. It can be seen in Figure 9 that the fractured planes are smaller in both the LD and BD than the WE43-T5 feedstock, which is caused by the reduction in grain size caused by the AFSD process. In addition, the fractography in Figure 9 for the BD suggests that interlayer defects or weakened metallurgical bonding were the cause of the low elongation to failure in the builds, as the dimpling present on the surface shows that the AFSD WE43 material is not failing due to brittle fracture as the macroscopic flat planar fracture would suggest.

Figure 10 shows representative fracture surfaces of the fatigue-tested specimen and offers insights into the effect of defects from the AFSD process during the crack initiation stage of the specimen.
In Figure 10, the WE43-T5 feedstock shows typical fatigue crack growth behavior across all stress levels as the cracks are observed to have grown from slip bands formed at the surface of the specimen before propagating to failure in a fast fracture region with signs of twinning near the crack initiation point. The faceted crack initiation appearance has been seen in previous work on WE43-T5 fatigue, as well as similar magnesium alloys being oriented toward the plane of maximum shear and was larger than the average grain size showing signs that slip is occurring across multiple similarly oriented grains and causing fracture [44,52]. This mechanism has been shown to most commonly occur at twin boundaries that can form from both the manufacturing process as well as during fatigue to accommodate the plastic strain necessary, as has been studied to explain the loading anisotropy seen in strain-controlled fatigue of magnesium alloys [53,54]. Twin boundaries function as stress concentrations, and they commonly form crack initiation sites in Mg alloys. The HCP crystal structure provides a limited number of slip planes, causing the formation of twin boundaries that allow the necessary deformation to initiate a crack [41,53,55,56].

The fractured LD specimens display crack initiation from near-surface twin boundaries as well before entering a flat, fast fracture regime early in the crack growth area of the build. The amount of twinning around the initiation was reduced compared to the wrought material and is potentially due to the grain size refinement inherent in the AFSD process allowing for a slip-dominated compression rather than twinning as preferred by larger grains [57]. Interestingly, the LD specimen fatigue tested at 207 MPa showed preferential crack growth around protrusions that resemble the features on the tool but were not a significant source of stress to initiate the crack in this region.

All BD specimens exhibit a flat fracture surface, along the plane of maximum tensile stress, with the 138 MPa specimen being the only one seen to initiate a crack from a near-surface particle. The 207 MPa specimen was tested at over 90% of its UTS, so resultantly, microvoid coalescence is seen across the entire fracture surface and likely initiated near the center of the specimen due to the stress triaxiality and caused rupturing of the matrix rather than initiating a crack as the other specimens did. The BD specimen also shows flow lines from the manufacturing process that are signs that the fracture occurred along a layer interface.

4. Conclusions

In this research, a parametric study and fatigue behavior of AFSD magnesium alloy WE43 were studied for the first time. Based on the results from this research, the following conclusions are drawn.

It was observed in this study that WE43 has a narrower processing window compared to aluminum alloys deposited using AFSD.

The parameters used on WE43 AFSD Build 8 in this study provided a well-consolidated build without any macroscopic defects such as galling or excess flash. In particular, build
8 exhibited a very refined, homogenous microstructure when compared to the WE43-T5 feedstock resulting in a reduction in average grain size from 45 to 2.7 \( \mu m \), respectively.

The acceptable parameters from Build 8 were used to create a bulk WE43 deposition to examine the orientation influence in quasi-static and fatigue behaviors. The average grain size from the top to the bottom of the deposit was considered consistent and homogeneous. A 90% reduction in grain size was observed from 45 \( \mu m \) to about 4.5 \( \mu m \) when comparing the WE43-T5 feedstock to the bulk WE43 deposit.

A consistent hardness from the bottom to the top of the deposition was measured throughout the bulk WE43 deposition. The quasi-static tensile results from the LD show a decrease in YS and UTS with an increase in ductility when compared to the WE43-T5 feedstock. The BD shows a similar YS and UTS to the LD but a significant decrease in ductility when compared to the LD and the WE43-T5 feedstock. However, both the LD and BD exhibit an increase in mechanical performance when compared to WE43 as-cast material.

The fatigue life of the bulk WE43 deposition in the BD and LD orientations was less than the WE43-T5 feedstock in the low cycle regime. However, in the high cycle regime, the LD and BD exhibited a comparable fatigue life to the WE43-T5 feedstock.

The bulk WE43 deposition monotonic tensile LD and BD fracture surfaces show microstructural signs of ductile failure occurring along the plane of maximum normal stress.

Fractography of the fatigue specimen shows that the LD specimen experienced crack initiation at twin boundaries similar to the WE43-T5 rolled plate, while the BD demonstrated ductile failure across the entire fracture surface in the low cycle regime, with the high cycle regime displaying typical near-surface crack initiation.

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Appendix A

Table A1. Process parameters for all WE43 Builds.

| Build Number | \( \omega \) (RPM) | \( F \) (mm/min) | \( V \) (mm/min) | Deposition Ratio (V/F) | Macro Defects | Hardness (Hv) |
|--------------|-----------------|-----------------|-----------------|----------------------|---------------|---------------|
| 1            | 325             | 50.8            | 101.6           | 2.00                 | Galling/Flash | X             |
| 2            | 400             | 76.2            | 101.6           | 1.33                 | No Bonding    | X             |
| 3            | 325             | 50.8            | 152.4           | 3.00                 | None          | 82.9          |
| 4            | 325             | 50.8            | 127             | 2.50                 | Flash         | 79.5          |
| 5            | 325             | 101.6           | 101.6           | 1.00                 | Flash         | X             |
| 6            | 325             | 101.6           | 254             | 2.50                 | Not Smooth    | X             |
| 7            | 325             | 152.4           | 203.2           | 1.33                 | Galling/Flash | X             |
| 8            | 325             | 63.5            | 152.4           | 2.40                 | None          | 82.0          |
| 9            | 325             | 152.4           | 254             | 1.67                 | Galling/Flash | X             |
| 10           | 350             | 50.8            | 101.6           | 2.00                 | Flash         | 80.0          |
| 11           | 350             | 50.8            | 152.4           | 3.00                 | Flash         | X             |
| 12           | 350             | 101.6           | 101.6           | 1.00                 | No Bonding    | X             |
| 13           | 350             | 101.6           | 254             | 2.50                 | No Bonding    | X             |
| 14           | 350             | 152.4           | 203.2           | 1.33                 | Flash         | X             |
| 15           | 350             | 152.4           | 254             | 1.67                 | Galling/Flash | X             |
| 16           | 375             | 50.8            | 101.6           | 2.00                 | Flash         | 82.3          |
| 17           | 375             | 50.8            | 152.4           | 3.00                 | Flash         | 76.4          |
| 18           | 375             | 101.6           | 101.6           | 1.00                 | Galling/Flash | X             |
| 19           | 375             | 101.6           | 254             | 2.50                 | Flash         | X             |
| 20           | 375             | 152.4           | 203.2           | 1.33                 | No Bonding    | X             |
| 21           | 375             | 152.4           | 254             | 1.67                 | Galling/Flash | X             |
| 22           | 400             | 50.8            | 101.6           | 2.00                 | Flash         | 84            |
| 23           | 400             | 50.8            | 152.4           | 3.00                 | Galling       | X             |
| 24           | 400             | 101.6           | 101.6           | 1.00                 | No Bonding    | X             |
| 25           | 400             | 101.6           | 254             | 2.50                 | No Bonding    | X             |
| 26           | 400             | 152.4           | 203.2           | 1.33                 | No Bonding    | X             |
| 27           | 400             | 152.4           | 254             | 1.67                 | No Bonding    | X             |
| 28           | 375             | 101.6           | 203.2           | 2.00                 | No Bonding    | X             |

The colors of the build number in Table A1 correlate to the viability of a parameter’s future use, depicting well-consolidated builds (gray), minor macroscopic defects (blue), and significant macroscopic defects (red). Table A1 also includes the deposition ratio (V/F), which has been reported in Phillips et al. [20] to be a crucial variable in the usefulness of depositions.

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