

Article

Elucidating the Effects of Material Flow from Deposition Offset on AFSD Repair of AA7050

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Abstract: In this work, the effects of tool bias as a processing parameter on an additive friction stir deposition repair of AA7050-T7451 plates were investigated. In this study, the asymmetrical material flow effect was assessed by subjecting a machined groove plate to different tool biases during the AFSD process. The tool bias effectiveness on repairs was quantified through mechanical testing and destructive and non-destructive evaluation. Monotonic tensile tests conducted in parallel with a digital image correlation method captured the mechanical performance of the repairs and the local strain effects of the heat-affected zone. X-ray computed tomography images of the different tool bias repairs were analyzed for any voids or defects to measure the overall bonding effectiveness. The results suggest that the advancing side tool bias had adequate bonding with the substrate, which yielded improved mechanical performance compared to the centered and retreating side depositions.

Keywords: solid-state additive manufacturing; additive friction stir deposition; repair AA7050; tool offset effects; material flow quantification



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1. Introduction

The aerospace industry requires materials with high strength-to-weight ratios for many applications. While steels are known for their high strength, they are often not selected for many aerospace applications because of their high density [1,2]. Instead, high-strength aluminum alloys, like the precipitation-strengthened 7xxx series, are utilized in the structural components of aircraft [3]. However, issues arise with these alloys when repairs are needed for a compromised component. Fusion-based repair methods, like Gas Tungsten Arc Welding (GTAW) on AA7050, can produce increased porosity, hot cracking, liquation cracking, entrapped porosity, and weakening in the area surrounding the repair, resulting in the characteristic low weldability of 7xxx series aluminum alloys [4–11]. AA7050, as an aerospace alloy, derives most of its strength from the formation of η , η' , and Guinier–Preston (GP) zones through their ability to inhibit dislocation motion [12–14]. These precipitates will re-dissolve and re-precipitate depending on the temperature, affecting the mechanical strength of the aluminum. For example, GP(I) zones have been seen dissolving back into solution at 100 °C, with GP(II) zones doing the same at 125 °C, and they are both re-precipitated as η' and η phases at higher temperatures (130–290 °C) [12]. This process

can dramatically affect the strength of alloys such as AA7050, which derives most of its strengthening from these precipitates and thus is temperature-sensitive [13,15]. Significant reductions in the strength of a material can have catastrophic consequences on performance, and thus methods of repair that minimize any deleterious effects on the material are needed. As many of these issues arise from the material's solidification after melting, repair methods that occur in the solid state without liquid-to-solid-phase transformations, such as AFSD, are necessary.

Traditionally, solid-state processing for high-strength aluminum alloys through friction stir welding/processing (FSW/P) provided a method for joining and repairing materials with many advantages over its fusion-based processing counterparts. When repaired by FSW, AA7050 has exhibited reduced porosity, no hot cracking or liquation cracking, and a reduced HAZ compared to the fusion-based repair methods [16,17]. In addition, since FSW is solid-state, the microstructure of the weld zone typically undergoes significant grain refinement, which can lead to increased strength and improved fatigue properties with post-processing [12,18–20]. However, as the FSW process does not introduce new material, FSW repairs are not ideal for repairs that require filler material, such as damage from gouges or loss of material from galvanic corrosion.

AFSD is a solid-state process similar to the physics of the FSW process but different in that the feedstock is directly deposited on the material in layers, enabling 3-dimensional metal printing of AA7075 in a rectangular cuboid shape formed by stacking multiple coplanar layers, AA7050 in a cross shape, or AA6061 in a cylindrical shape, as carried out by Avery et al., Mason et al., and Philips et al., respectively [21–23]. AFSD repairs provide many of the same benefits as FSW in terms of eliminating solidification cracking and porosity, grain refinement, and even increased yield strengths relative to FSW material [24]. There have been numerous AFSD volumetric repairs on aluminum alloys of simulated damage of different groove geometries and through holes, with varying results and process parameters. Studies with AA6061 feedstock deposited on an AA6061 substrate and cast aluminum (Mic 6) from Martin et al. [25,26] provide insight into the general mechanical characteristics such as fatigue, tensile strength, and the microstructure properties of AFSD repairs. The repairs were able to fill the different milled groove geometries up to a certain depth level of 2–3 mm, but deeper levels exhibited evidence of inadequate material mixing, and visible voids along the groove interface were observed. The same trend appeared for the repair study on an AA7075 aluminum alloy in which Griffiths et al. studied varying width groove channels and holes [27]. Avery et al. later explored post-processing techniques where a heat treatment was used to increase the mechanical properties of the post-deposition repair of 7075 on a groove [24]. These results demonstrate that AFSD is a suitable candidate as a repair technique, but further investigation is needed to understand the repair application for different geometries, especially for deeper grooves and channels where the deposits do not adequately fill the entire repair at the groove boundaries.

The issue of inadequate mixing/bonding within the deeper layers of the channeled grooves for AFSD repairs can be attributed to the different process parameters influencing the material flow under severe plastic deformation and shearing of the feedstock along the tool–substrate interface. Perry et al. [28,29] studied the morphological and microstructural properties of AFSD depositions and observed the material flow and the deformation mechanism via X-ray computed tomography (CT) with AA2024 and AA6061. In both studies, AA2024 was either used exclusively as the main feedstock printed onto an AA6061 substrate or it was the embedded tracer material within an AA6061 feedstock. The dissimilar materials allowed for enhanced visualization and quantification through X-ray CT. Due to the dynamic nature of the rotation and simultaneous travel of the tool, the substrate–tool interface has a distinct morphology and an asymmetric mixing character-

istic. The two sides of this asymmetry, which are affected differently by the friction stir process, are referred as the “advancing side” (AS) and the “retreating side” (RS). The AS is the side of a deposit where the tool’s traversing and tangential direction are in the same direction. The RS is the region where the mentioned directions are opposing each other. It is known that the AS experiences a higher degree of plastic deformation and frictional heating. Stubblefield et al. [30,31] observed an AS bias material flow influence and a 50–100 °C temperature differential across the AFSD tool face through embedded thermocouples in a substrate of the experimental portion, as well as in coupled computational smooth-particle hydrodynamics (SPH) thermo-mechanical simulations. Their other study similarly evaluated the AFSD deposition material flow both experimentally and computationally through SPH with the use of a tracer material within the feedstock and X-ray CT analysis. The SPH simulations were consistent with the experimental findings. It was found that the AS had more dynamic mixing and material accumulation, thus producing an asymmetric general flow of the deposited material onto the substrate.

There are limited studies in FSW that have implemented and examined the effects on the mechanical and microstructure of tool bias (offset) on welds. Memon et al. were able to avoid tunneling defects and to achieve higher tensile strength values when a tool bias was applied towards the AS on an AA6068 T-joint weld with FSW. A CFD simulation also indicated that the strain rates were higher on the AS, suggesting that the AS promoted greater material flow and mixing between the tool pin and the substrate [32]. Kasman et al. had similar results with FSW overlap of AA7050 but noticed that higher RPMs were better suited for tool bias when comparing results from lower RPMs [33].

This study proposes to evaluate the effect of implementing different tool biases (offsets) on the AFSD process to a grooved AA7050 plate to simulate the repair of a damaged component. Leveraging the asymmetric nature of AFSD repairs by biasing (offsetting) the tool centerline from the repair centerline has yet to be analyzed. Thus, this paper’s focus is to quantify the mechanical performance and microstructural properties of the repairs with different tool biases as an applicable parameter to consider for repairs. The mechanical properties were quantified with quasi-static tensile and microhardness tests. Optical microscope, scanning electron microscopy (SEM), X-ray computed tomography (CT) scans, and digital image correlation (DIC) techniques were used to observe the influence of different tool biases on AFSD repairs compared to the traditional centered (no bias) processing approach.

2. Materials and Methods

2.1. Process Parameters and Samples

For this study, a B8 AFSD machine (MELD Manufacturing, Christiansburg, VA, USA) was used to deposit graphite-coated 9.35 mm square AA7050-T7451 feedstock rods onto two 305 mm long by 228 mm wide by 6.4 mm thick plates of AA7050-T7451. The plates were milled with a 6.35 mm ball to create a 20 mm wide by 1 mm deep groove. The groove geometry was selected to simulate a corrosion removal technique for corrosion pits on aluminum alloys that is recommended by the Federal Aviation Association advisory circular 43-4B [34]. Figure 1 presents the experimental setup of the repair plate with the corresponding deposition path and the used tool offset distance values. Two separate repair plates were used, one for each tool bias offset distance (6.4 and 7.1). The displacement-controlled deposition parameters consisted of a tool spindle rotation speed of 225 rpm, an actuator feed rate of 50.8 mm/s, and a traverse velocity of 25 mm/min at a fixed single-layer height of 2 mm, as presented in Table 1. To achieve the prescribed actuator feed rate, an actuator applied force directly to the feedstock while all other parameters were held constant. These parameters were chosen based off of previous experimental trials, which

aimed to prevent excess flash/material outside the tool face width. The dwell regions of the deposit, shown as gray in Figure 1, were excluded from any microstructural or mechanical testing or analysis in order to avoid sections that were exposed to excess frictional heat produced by the 38 mm hollow featureless rotating tool. Only the steady-state regions (colored blue, red, and green) were considered for testing and analysis, as these were the areas where the tool had traversed in a steady-state manner and did not have direct additional frictional heat input from the dwell regions.

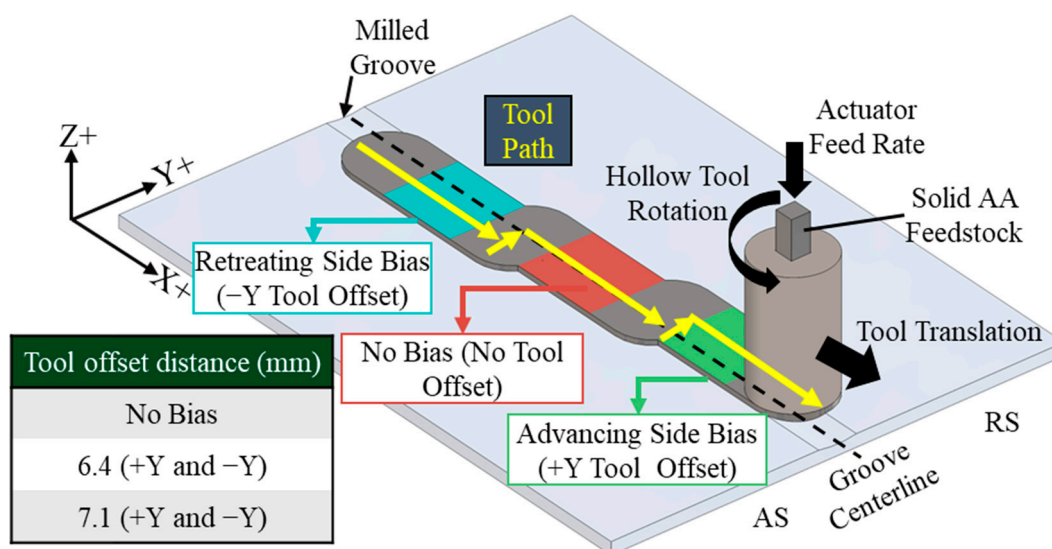


Figure 1. Experimental setup for AFSD groove repair while implementing tool offset from groove centerline.

Table 1. AFSD 7050 repair process parameters.

Specimen ID (Tool Bias)	Plate ID	Tool Rotational Rate (RPM)	Actuator Feed Rate (mm/min)	Traverse Velocity (mm/min)	Layer Height (mm)
AS 7.1	1	225	50.8	25	2
RS 7.1	1	225	50.8	25	2
No Bias	1 and 2	225	50.8	25	2
AS 6.4	2	225	50.8	25	2
RS 6.4	2	225	50.8	25	2

A single prescribed tool offset distance and a centered region were designated for each of the deposition's paths, as illustrated in Figure 2. Each deposition consisted of three 76 mm long sections, which were divided into RS bias, no bias (centered), and AS bias, in that order. Two AA7050 plates were used to isolate the two designated offset distances (6.4 mm and 7.1 mm), which represents 50% and 56% of the feedstock width. These distance values were obtained through prior experience and experimental trials that aimed to achieve a balance between the tool face coverage and preventing the feedstock from being positioned directly outside the groove to avoid excessive actuator forces. The tool offset consisted of the tool centerline positioned at an offset of the groove centerline along the Y direction during the deposition. Figure 2a shows the RS bias configuration where the tool centerline is on the negative direction of the Y direction, which exposed the groove to the RS of the tool. Figure 2b presents the commonly used centered, or no bias, configuration, where the tool centerline is coincident to the groove centerline. Figure 2c presents the AS bias configuration, where the tool centerline is on the positive side of the Y direction, which exposed the groove to the AS of the tool.

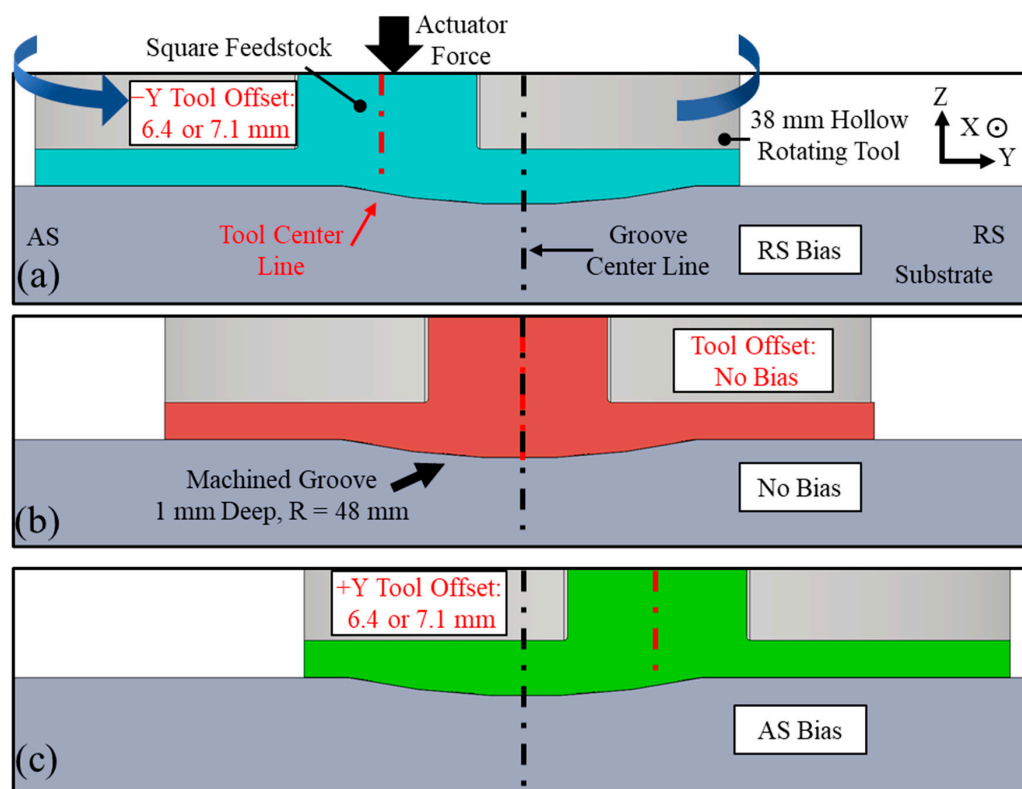


Figure 2. Schematic of a single deposit cross-section showing the AFSD tool offset position relative to the machined groove center line: (a) negative, (b) zero, or (c) positive values of the tool offset indicate that the groove is exposed to the retreating side, center, or advancing side of the tool, respectively.

2.2. Experimental Methods

Metallographic cross-section samples were collected from the steady-state regions of each tool bias deposition (AS, RS, and centered) for all tool offset distances to obtain optical micrographs of the repaired regions. The samples were hand-ground and polished sequentially from European Graded P320 to a 1 μm diamond suspension. The optical micrographs were captured with a Keyence VHX-7000 digital microscope (Keyence Corporation, Osaka, Japan) at 150 $\times$ and 400 $\times$ zoom levels.

Computed tomography (CT) scans were performed via the North Star Imaging (NSI) X-3000 microfocus X-ray system (North Star Imaging, Rogers, MN, USA). For all scans, a voltage of 100 kV and current of 200 μA , with a focal spot size of 20 microns, was used to generate an X-ray beam with a voxel size of 19.19 μm . NSI's inhouse version i4.0 reconstruction software was used, following CT scans, to select the sharpness and beam-hardening settings and to output an image file for each individual scan. The files were further analyzed with the Dragonfly artificial intelligence (AI) version 2022.2 software segmentation feature trained to differentiate and calculate void volumes within the repair via the difference in grayscale values of the CT scans.

A representative Vickers hardness test was performed on the centered (no tool offset) region with an Emcotest Durascan Hardness Tester (EMCO-TEST Prüfmaschinen, Kuchl, Austria) per ASTM 384-22 on a 76 $\times$ 6 mm grid with a 1 $\times$ 1 mm indent spacing and an applied force of 1 kg force (HV 1) for 10 seconds. For the grain size analysis, there were three regions of interest: the HAZ, the AFSD repair region, and the base metal outside of the HAZ. The sample was ground and polished to a 1 μm diamond suspension finish and then vibratory polished to a 0.03 μm finish using colloidal silica. A Versa 3D focused ion beam scanning electron microscope (Thermo Fisher Scientific, Waltham, MA, USA), with 30 keV, a spot size of 9, and step sizes of 1 μm and 0.3 μm for the substrate and AFSD–

interface sections, respectively, was used to collect the electron backscatter diffraction (EBSD) measurements (AMETEK, Inc., Berwyn, PA, USA). A grain dilation cleanup of a minimum of 10 pixels per grain was performed with the EDAX orientation imaging microscopy software version 8 (AMETEK, Inc., Berwyn, PA, USA), which produced grain size maps of the mentioned regions to quantify grain size.

To study the mechanical properties of all the tool offset distances and biases, modified ASTM E8 monotonic tensile specimens were machined out of the steady-state regions with a Mitsubishi MV1200 wire electrical discharge machine (EDM) (Mitsubishi Electric Corporation, Tokyo, Japan) with geometry as illustrated in Figure 3a. The specimens were extracted from the steady-state regions of each of the tool biases, with the specimen length perpendicular to the groove path and the center containing the AFSD repair. The deposited AFSD layers were machined flat, and the surfaces of each specimen were hand-ground with European Graded 1200 P sandpaper to achieve a uniform finish across the gage section. The 50.8 mm length of the gage section was chosen to include the HAZ and avoid fracture near the grip section during the tensile testing. Each specimen was spray painted with matte white and black paint to achieve a speckle pattern that achieves 50/50 coverage with equiaxed spot size. Figure 3b displays how the specimens were placed in an MTS Model E45 electromechanical load frame, fitted with a 100 kN load cell, and tested with a crosshead speed of 0.07 mm/s. The tensile specimens were orientated with the groove repair facing a Zeiss Aramis Adjustable 30 mm sensor (Carl Zeiss AG, Oberkochen, Germany) that recorded each tensile test, while the opposite side was attached with a 50.8 mm MTS model #63436E-24 gage extensometer. The video images were then processed through the ZEISS GOM DIC program to retrieve the localized strain values during the tests.

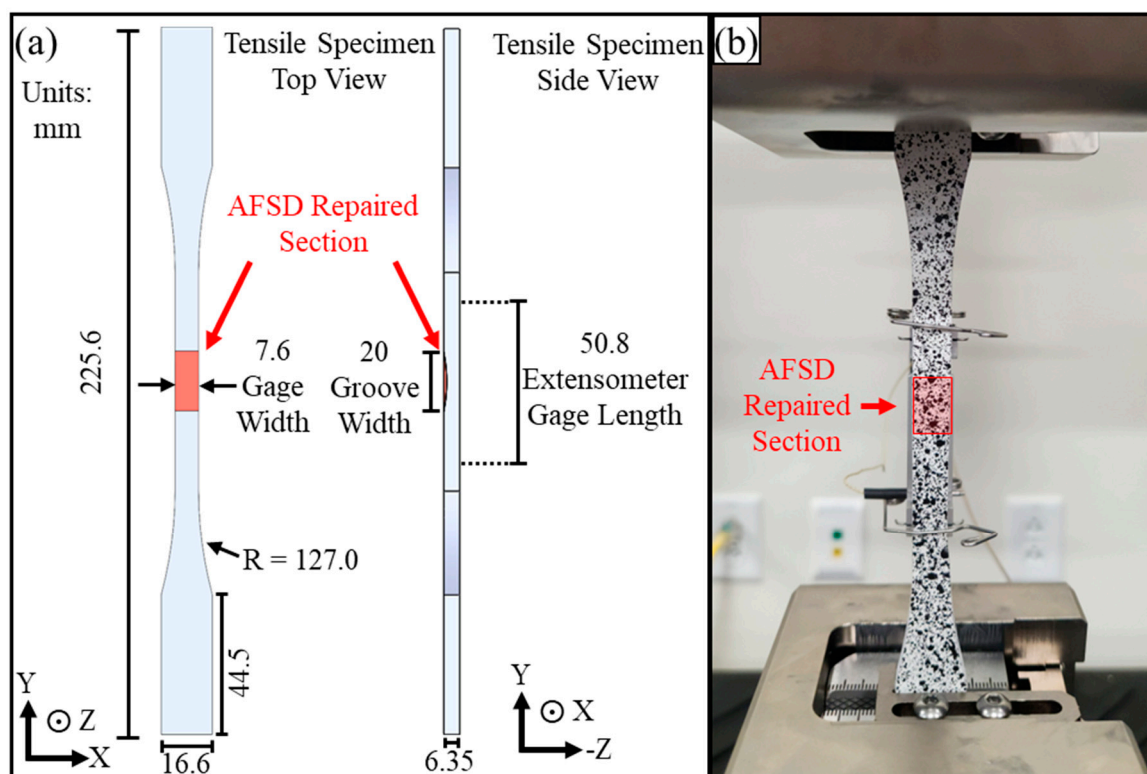


Figure 3. (a) Monotonic quasistatic tensile specimen geometry used for all tool offsets and biases. The red section indicates the repaired region. (b) white and black speckle pattern painted tensile specimen loaded in the EM frame from the viewpoint of the DIC sensor system, which allowed real-time full-field strain measurements through the software.

3. Results and Discussion

Figure 4 presents the overhead view results of all the tool offsets and biases final AFSD repairs along the grooved plates. Figure 4a shows how the RS bias deposition did not fully fill the entire groove volume since a portion of the groove is still visible along the RS of the groove. This portion of exposed groove increased as the tool offset distance towards the AS increased. The largest RS bias tool offset (-7.1 mm) produced a flash that cooled and resulted in a thin fin-like feature that did not bond to the groove. In contrast, Figure 4b,c display the AS; no bias depositions filled the groove, and there are no visible gaps or exposed groove sections. In terms of visual volumetric restoration, the AS and no bias depositions were the most effective.

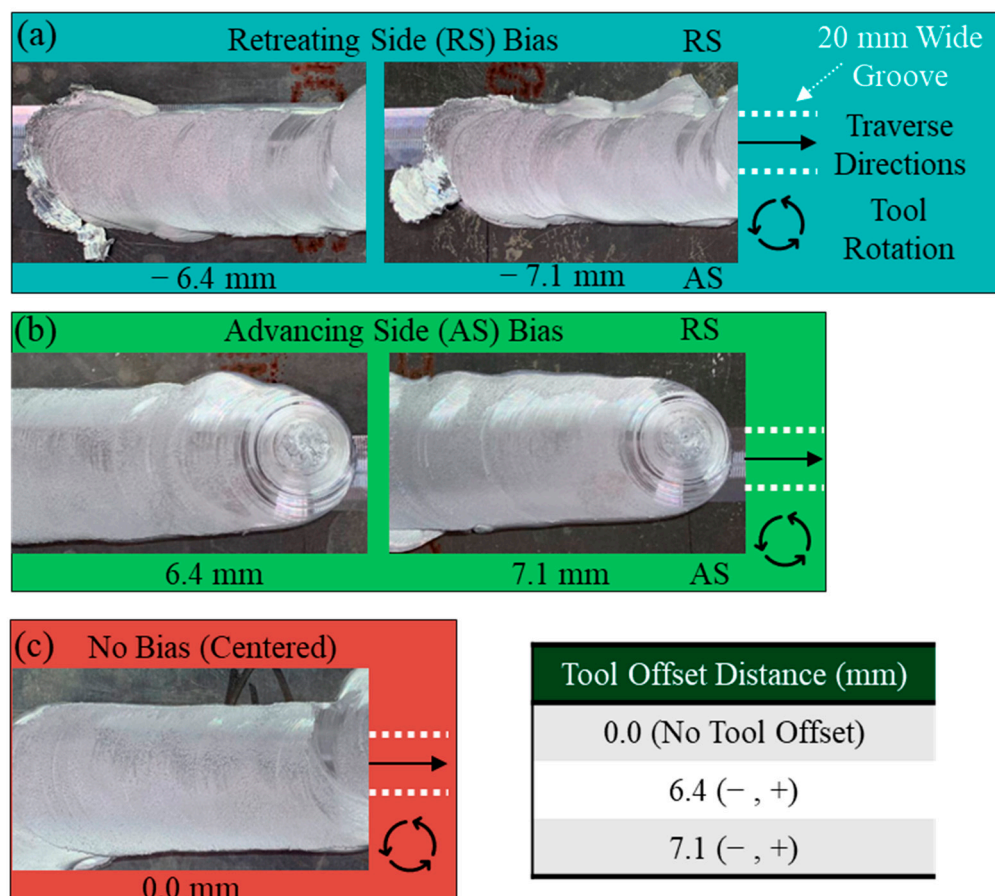


Figure 4. Results of as-processed depositions made with different tool offset distances that filled the groove with (a) retreating side bias, (b) advancing side bias, and (c) no bias orientation.

Figure 5 depicts the optical micrographs of the polished cross-section samples of all the tool offsets and biases post-deposition, accompanied with a higher magnification micrograph of the groove and substrate interface. In the RS bias depositions, as shown in Figure 5a,b, there are visible continuous voids along the groove–substrate interface and areas that were not filled during deposition. However, the no bias and AS bias depositions, Figure 5c–e, had no visible voids or deposit separation along the repair interface. The asymmetric nature of the deposited material across the different tool offset biases to fill the groove is apparent by the observed lack of bonding between the substrate and deposit when the RS bias was employed. Moreover, the RS bias deposits generated more flash, which increased with a greater tool offset distance. This additional flash generation could be attributed to the fact that the deposited material has less mixing,

leading to less heat generation, and thus does not plastically flow as easily when compared to the AS bias deposits.

Tool Bias

(mm)

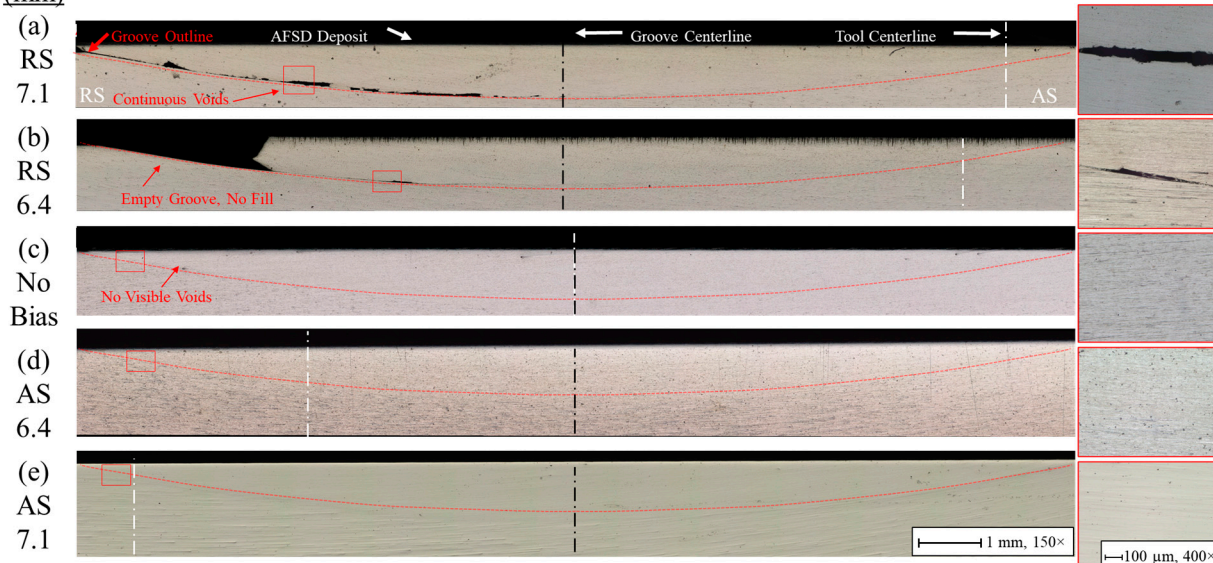


Figure 5. Optical micrographs of the cross-section samples of (a) −7.1 mm RS bias deposit, (b) −6.4 mm RS bias deposit, (c) centered no bias deposit, (d) 6.4 mm AS bias deposit, and (e) 7.1 mm AS bias deposit.

The results of the X-ray CT scans and 3D reconstruction are presented in Figure 6 for the different tool offset distances and biases. Figure 6a shows the geometry of the samples that were evaluated and analyzed by the Dragonfly software to identify voids throughout the multiple scans within the samples. It is also the reference point for Figure 6b,c, which are the scanned samples of the AS bias 7.1 mm tool offset and RS bias 7.1 mm tool offset, respectively. These samples were chosen to quantify both extreme cases of tool offset that were implemented for each tool bias. Figure 6b depicts how the software was not able to detect any voids larger than $\sim 40 \mu\text{m}$ (based on double the $19.19 \mu\text{m}$ micron voxel size used) on the AS bias deposition sample, suggesting favorable bonding between the deposit and substrate. However, from Figure 6c,d, it is evident that the RS bias had insufficient bonding to the substrate, which yielded a void volume fraction of over 1.4% within the groove repaired region that was analyzed. All the voids detected were concentrated on the RS half of the sample up to the centerline of the groove for the RS bias deposit, while the AS had no voids. This is likely due to the extra pressure and mixing under the region of the feedstock, the effect of which is subsequently reduced at increasing radial positions relative to the tool centerline.

Figure 7a displays the generated Vickers hardness maps for a centered (no tool offset) repair. The wrought plate hardness was measured to be 161.8 HV. However, post-repair, the hardness map reveals the weakened HAZ and its boundary, which is approximately 45 mm wide. This is wider than the tool face, which is 39 mm. By observing the tool shoulder boundary, the HAZ on the AS extends further from the tool shoulder, while the HAZ on the RS does not extend to the tool shoulder, suggesting higher frictional heat on the AS. The average hardness reduction for the HAZ and the groove area was approximately 35% and 12%, respectively. This was expected since the heat input and temperatures that approached solutionizing levels are known to coarsen the η and η' strengthening precipitates, resulting in lower hardness and lower strength in the HAZ [12,13]. Figure 7b shows the EBSD grain size maps of the unaffected substrate, which retained the hardness

values of wrought material. Large 100 μm columnar grains were present, which is common for rolled plates. Figure 7c presents the repaired interface in which the substrate rolled plate large columnar grains have now broken into smaller grains and the refined AFSD deposit has the characteristic fine equiaxed grains. Figure 7d shows the fine equiaxed grains of the AFSD process, which are in the range of 3.4 μm in size, which retained part of the original feedstock T6 strength.

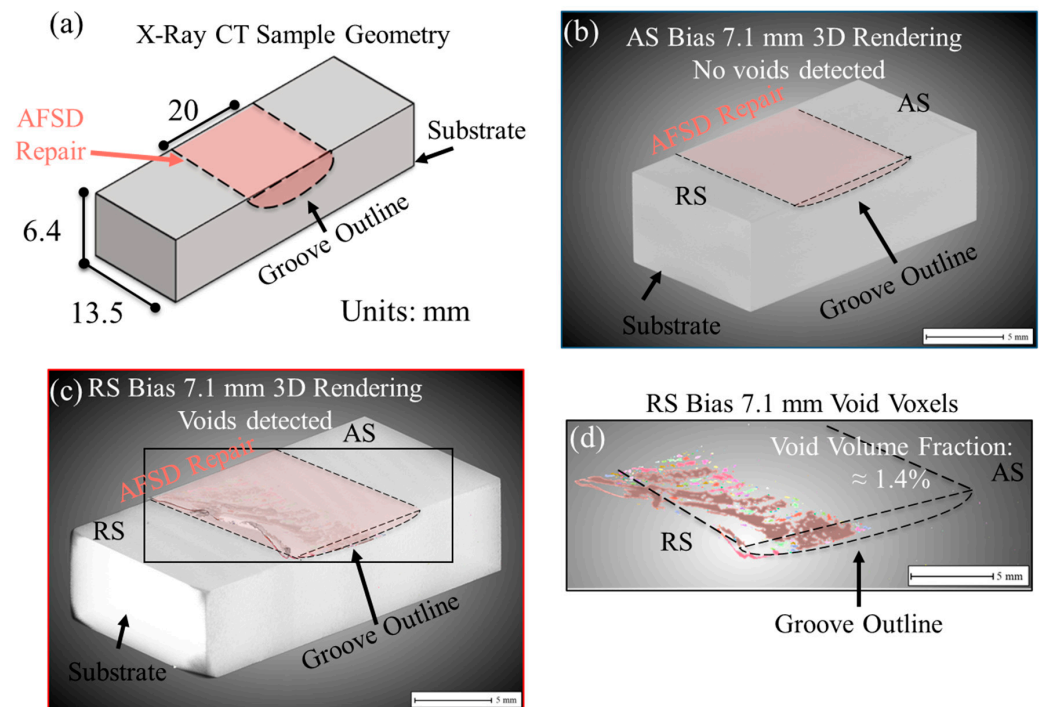


Figure 6. (a) Schematic of the X-Ray CT 3D sample used to quantify the void volume in the repair region of depositions that used (b) AS bias 7.1 mm orientation and (c) RS bias 7.1 mm orientation and the (d) magnified rendition of the void volume found in the RS bias 7.1 mm sample.

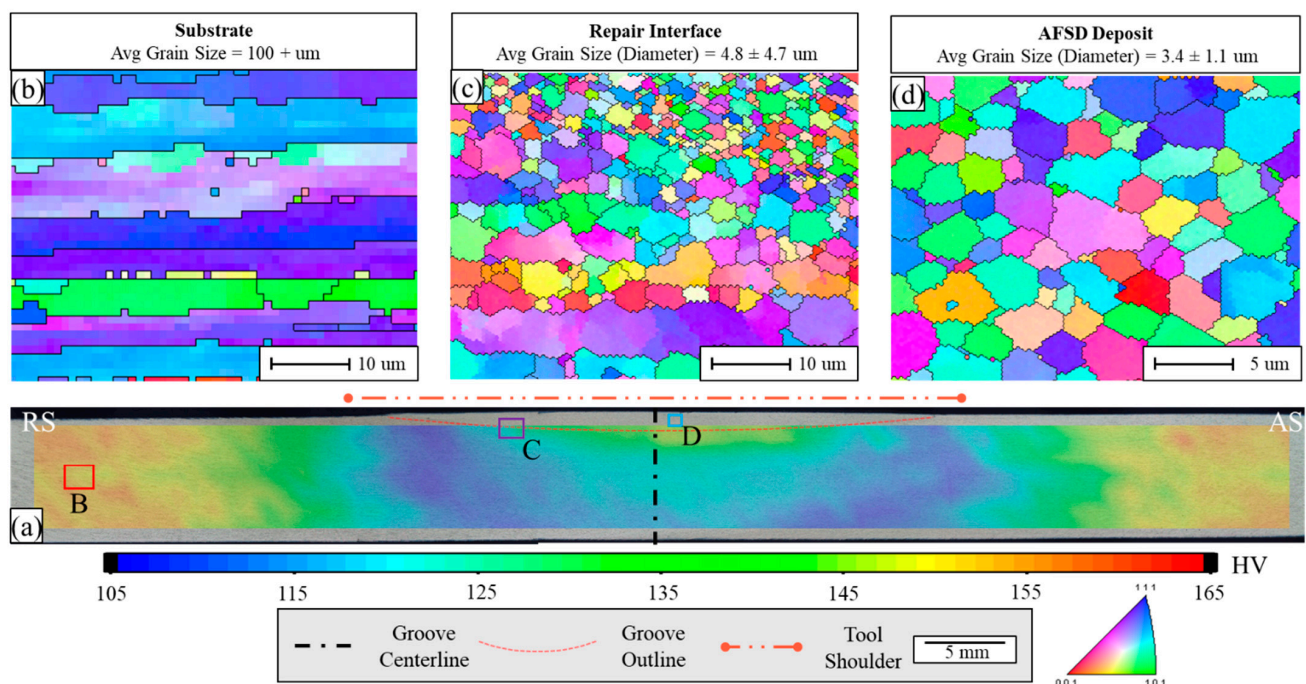


Figure 7. (a) Hardness map overlay on a centered repair cross-section with EBSD grain size maps of the (b) base metal away from the HAZ (c) repair interface and (d) AFSD deposit region.

Figure 8a and Table 2 present the results of the monotonic tensile tests of each condition of the repaired specimens, which include AS, RS, and no bias repairs. The ultimate tensile strength (UTS) and yield strength (YS) of a standard AA7050-T7451 wrought plate are included for reference. To evaluate how effective the repairs were compared to a wrought specimen, the repair efficiency was calculated as the ratio of the tested samples' mechanical performance to that of the wrought sample. The measured stress–strain responses for all the repaired specimens had a maximum UTS of 64–80% compared to wrought T7 for the RS bias and the AS bias, respectively. The overall decreased UTS and YS repair efficiencies was expected due to the HAZ and the bonding efficiency. The strain to failure repair efficiency values for the AS bias repairs were twice those of the RS bias repairs and slightly greater than the centered bias (~10%). The RS bias repairs had the lowest strain-to-failure values of 2.4–3.1%, which is a decrease of 78% and 72% for the -7.1 mm and -6.4 mm tool offset, respectively. The difference in the mechanical behavior can be attributed in the distinct failure modes observed from the sideview profile of the fracture surfaces of the RS and AS bias deposits (Figure 8b,c). The RS bias fracture occurred at the groove repair interface, with multiple fracture paths, and separation of the deposit from the substrate interface was observed. This separation most likely caused an increased stress concentration, and coupled with the weakened thermally softened base material, rapid fracture occurred with minimal necking. The AS bias fracture had a 45° shear plane fracture in the HAZ, away from the groove repair area. The HAZ is softened by the coarsening of the strengthening precipitates, allowing for dislocations to move freely rather than be impeded, which explains the increased ductility and lower overall tensile strength.

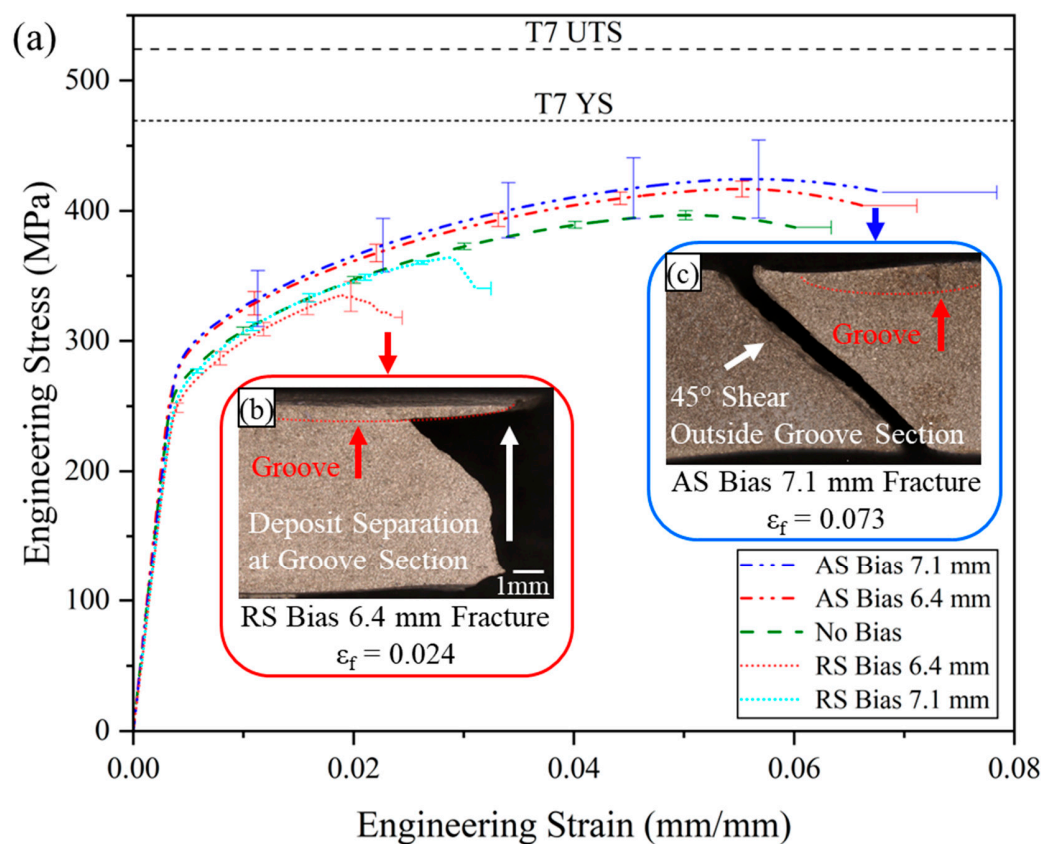


Figure 8. (a) Measured stress–strain response of the tested samples from all the tool offset and bias configurations with insets of the OM sideview profile fracture surfaces of (b) RS and (c) AS bias repair.

Table 2. Monotonic tensile properties of AFSD repairs and wrought specimens.

Specimen Tool Bias (mm)	σ_{ys} (MPa)	σ_{UTS} (MPa)	ϵ_f (%)	σ_{ys} Repair Efficiency (%)	σ_{UTS} Repair Efficiency (%)	ϵ_f Repair Efficiency (%)
AS 7.1	304 ± 24	424 ± 30	7.3 ± 0.7	65 ± 5	81 ± 6	71 ± 6
AS 6.40	300 ± 12	416 ± 6	6.9 ± 0.3	64 ± 3	79 ± 3	60 ± 3
0.00	280 ± 3	396 ± 4	6.2 ± 0.2	60 ± 1	76 ± 1	56 ± 2
RS 6.40	272 ± 5	335 ± 7	2.4 ± 0.1	58 ± 1	64 ± 1	22 ± 1
RS 7.10	278 ± 2	364 ± 1	3.2 ± 0.1	59 ± 1	70 ± 1	28 ± 1
Wrought (T7)	469	524	11			

Figure 9 contains the results of the DIC analysis for each of the tensile tests, revealing the localized strain on the surface of each of the tensile samples. The labels and values on the scale bar represent the localized point strain in the tensile direction, with a scale bar for each of the values. Value labels were placed on three specific locations of interest, which correspond to both edges of the HAZ and the middle gage section. All AS bias and centered repaired specimens exhibited a similar trend in which there was high strain localization on the HAZ edges, away from the groove boundaries. During plastic deformation, the HAZ regions remained at a higher state of strain than the gage section, until necking occurred, and the localized strain concentrated onto one side of the HAZ until ultimate fracture. At fracture, the local strain values (16–39%) were nearly four to five times greater than the reported axial gage elongation readings of the extensometer during the tensile test (2–7%), which is relatable to the values on other DIC tensile studies with FSW AA6061-T6 and AA2198 [35,36]. The high local strain values are directly related to the increased plastic deformation within the HAZ softened substrate that has lower mechanical properties than the original T7 temper condition. The RS bias local strain maps depict how the strain localized on the groove interface as the repair deposit separated as the tensile load was applied. The separation caused a shift in the load, which was concentrated along the reduced area from the groove section. The reduced area geometry likely caused an increased stress concentration, which resulted in a rapid, brittle-like fracture, which ultimately caused the 50% decrease in strain to failure compared to the wrought specimens.

Figure 10 depicts the SEM fracture surface images of both 7.1 mm tool offset biases (AS and RS) with higher-magnification images of surface features that depict distinct aspects of the fracture mechanisms for each offset bias. On a macroscopic level, the RS bias fracture surface had multiple fracture planes at different angles with sharp boundaries. However, the groove section (red semicircle) had a distinct planar surface and had fewer fracture paths observed since this area was not metallurgically bonded to the deposited AFSD region. Once the deposit separated from the groove, from insufficient bonding on the RS, this likely caused a stress concentration at the root of the groove, which lead to rapid fracture to initiate at this region. The AS bias fracture surface consisted of a single planar ductile shear-dominated feature in comparison, with fewer observed fracture paths than the RS bias fracture surface. Since fracture occurred outside of the groove area, there were no distinct features, and thus the surface was homogeneous, as the AFSD deposit had a metallurgical bond to the substrate. The higher-magnification image of the RS bias fracture surface showed instances of flat surfaces along with dimple-shaped structures that contain micro-voids, which is expected from tensile loads. The fracture path marks are long (over 50 μm) and have a general directional trend, which suggests intragranular fracture. These features contrast with the high-magnification image of the AS bias fracture surface. The dimple-shaped structures were more defined and larger than the dimples found on the RS bias fracture surface. This correlates to higher ductility, which was the case for the AS bias samples.

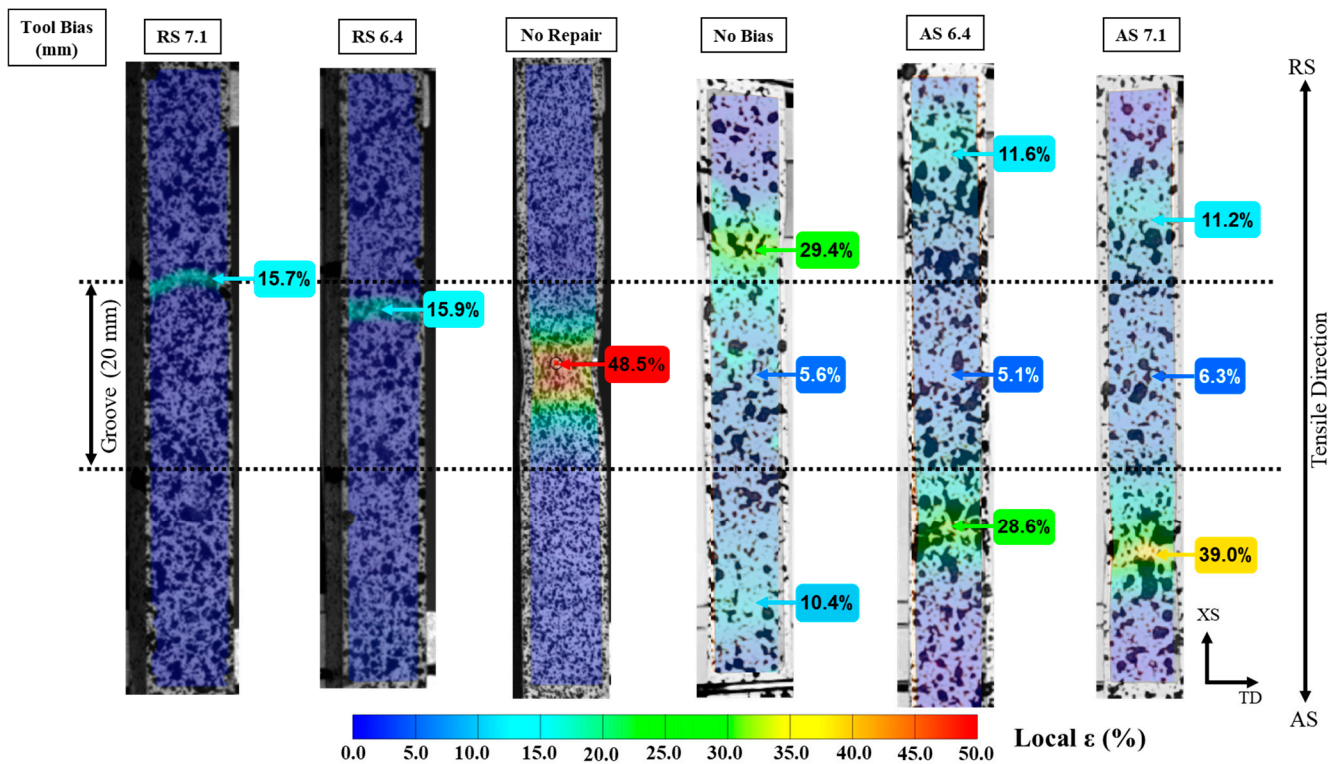


Figure 9. Surface strain localization maps of the entirety of the gage section generated by DIC during monotonic tensile testing for all the tool bias and offset samples.

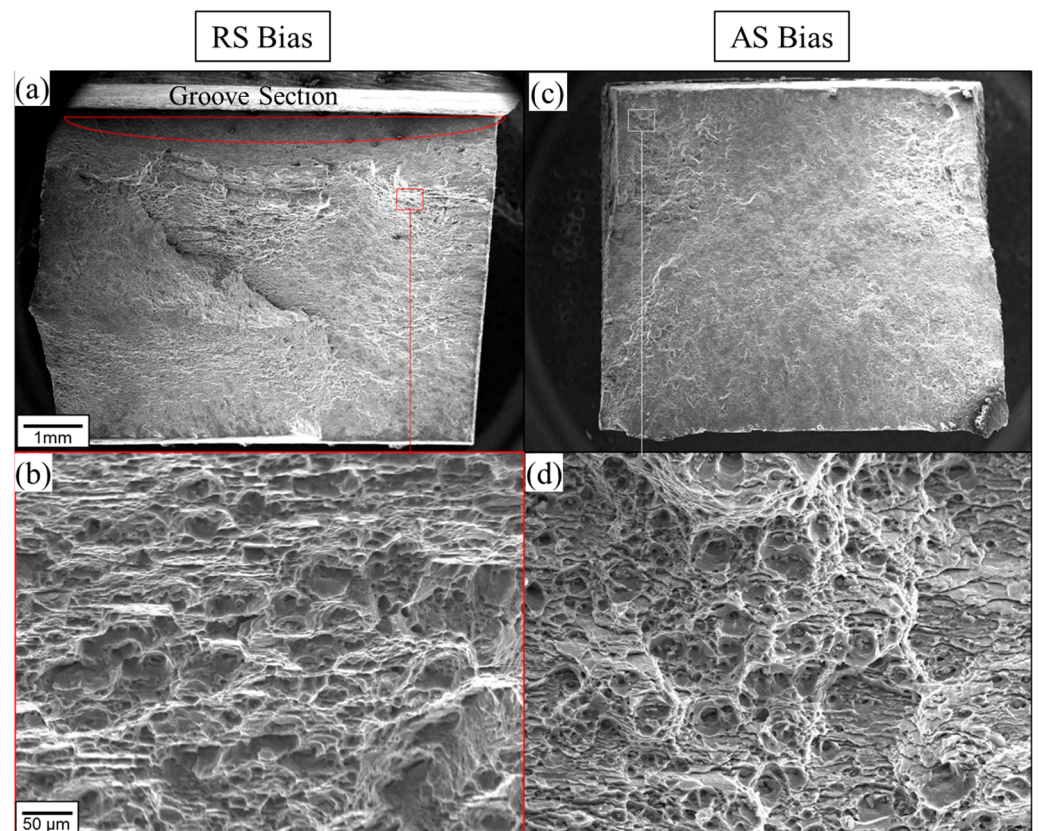


Figure 10. SEM images of the fracture surface of (a) a 7.1 mm RS bias tensile specimen with (b) higher magnification of a surface feature and the (c) fracture surface of a 7.1 mm AS bias tensile specimen with (d) higher magnification of a surface feature.

4. Conclusions

This study examined the effect of tool offset on a solid-state repair of AA7050-T7451 with the AFSD process. Microstructure characterization and mechanical testing coupled with enhanced optical and imaging techniques (CT and DIC) were employed to quantify the overall influence of tool offset on the material flow and final deposition outcome. From the results of the study, the following conclusions were drawn:

- AFSD was used to repair a machined groove while implementing tool offset as a novel processing technique. This approach improved the as-deposited mechanical performance, as evidenced by the varied failure modes, attributed to the distinct metallurgical bonding of the deposit–substrate interface.
- The no bias and AS biased tool offset repairs had no visual separation of the deposit or lack of bonding to the substrate. In contrast, the RS bias repairs showed multiple voids, a lack of bonding, and insufficient deposit coverage. CT scans revealed that these voids were concentrated along the RS of the groove interface, which accounted for up to 1.4% void volume fraction, suggesting a lack of material mixing due to lower frictional heating from the tool face.
- The EBSD scans revealed that the centered repair had a metallurgical bond with the deposited material. There was a mixture of refined equiaxed AFSD grains measuring 3.4 μm with elongated grains of the base material along the groove repair interface. However, the base material had a hardness reduction of up to 35% in the HAZ region, which extended to the width of the tool diameter.
- Through monotonic tensile tests with DIC, the tool offset showed different failure mechanisms due to the bonding efficiency. By implementing AS bias repairs, the UTS strength increased by nearly 27% and the ductility doubled when compared to the RS bias repairs. The AS bias and centered no bias repairs had strain localization and fracture paths along the HAZ, away from the groove edge. Tool offsets towards the AS (RS bias) caused rapid fracture, with the strain localized and concentrated at the groove interface as the deposit delaminated from the substrate. These results suggest that employing AS bias repair can provide a more effective and robust repair solution.
- The fractography of postmortem monotonic tensile tests highlights the distinct macro- and microscopic surface feature products of the different failure modes. On the macroscopic level, the RS had multiple fracture planes, more than the AS bias specimen, leading to the rapid fracture and low ductility. On the microscale, larger voids from within the equiaxed dimples on the AS specimen provide evidence of increased ductility and overall higher load-bearing capacity, evidenced by the nucleation, growth, and coalescence of voids.

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