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Proposed Hybrid Processes for Part Building Using Fusion Welding and Friction Stir Processing

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Abstract

It has been shown that a hybrid laser additive manufacturing and friction stir processing can deposit components with forged-like structures. This paper reports a hybrid fusion welding and friction stir process to create parts with quality structures. Combining traditional fusion welding and friction stir processing techniques for non-weldable aluminum alloys could facilitate the joining of difficult geometries in manufactured parts. This research illustrates mechanical property changes for non-weldable and weldable aluminum alloys. The Vickers hardness, and microhardness in the case of AA5052-H32, tensile strength and corrosion resistance of four processing states: base material, fusion welded material, friction stir welded material, and friction stir processed fusion welded material are studied for AA2024-T351, AA5052-H32, and AA7075-T651. This technology has applications to part building for large parts such as landing gear, and ship hulls; where traditional additive manufacturing processes would be excessively costly and time consuming. By joining larger pieces by such a hybrid process, a near net shape approach can be achieved on a large scale. This technology would remove the need for drilling and fastener use, plausibly increasing the strength of large part joints with complex geometries.

Introduction

Friction Stir Welding was developed in 1991 by The Welding Institute (TWI Inc.) specifically for the joining of aluminum alloys.[1] Today, friction stir welding can be used to join many different types of materials from plastics to super-alloys. While some aluminum alloys can be joined using traditional welding techniques, such as Gas Tungsten Arc Welding (GTAW), many of the aluminum alloys associated with aerospace materials cannot be welded. Alloys such as AA2024, and AA7075, cannot be welded, in any heat treatment, due to hot cracking and large decreases in material properties around the weld. However, AA5052 can be welded by traditional welding methods, the fact that it is a non-heat treatable alloy, only adds to the ease of fusion welding, providing that post-weld heat treatments and natural aging are not an issue.[2]

Friction Stir Welding (FSW) seeks to remove some of the adverse properties of fusion welding by employing the use of friction to create a solid state joining process. This means that heat is added gradually to the material, and no melting occurs. This method provides for no phase changes within the material, as well as creation of a joint between two plates, in multiple configurations.[1]

A need to improve the manufacturing methods used for joining aerospace grade aluminum alloys is relevant as the need for lighter, thinner sections of material are being used for increases in efficiency for aerospace applications. By eliminating other solid state joining processes, such as riveting, which creates stress concentrations, it could be possible to create more stable joints by creating a hybrid process between traditional fusion welding and FSW. This hybrid process provides a possibility of eliminating the clamping forces and distortion associated with FSW, as well as creating a post-processing technique for insufficient fusion welds of aerospace grade aluminums such as AA2024-T351, AA5052-H32, and AA7075-T651.[3] While the combination of fusion welding and friction stir welding has been studied in the past by a few groups, the study of aerospace grade materials has not been touched, largely due to the stigma surrounding the fusion welding of aerospace grade aluminum alloys. Although the hybridization of fusion welding and friction stir welding is not a new technology, the introduction of this processing combination is new for aerospace grade aluminum alloys. The materials previously studied: AA2219, AA5083-H321, AA6082-T6, SS304L, and SS400, are all weldable aluminum and stainless steel alloys.[16-23] The analysis of the hybrid process done in the embodiment of this research incorporates the weldable aerospace grade AA5052-H32 alloy, and non-weldable aerospace grade alloys: AA2024-T351 and AA7075-T651. The study of FSP of fusion welds, in the past, has focused mainly on the surface processing of the fusion welds. This research studies the friction stir processing of the entirety of the weld nugget within the joint, creating a more homogenous mixture, as a traditional friction stir weld joining process would do. The processing of the entire joint creates a better opportunity for non-weldable alloys to use this hybrid process.

The work provided is composed of a mechanical property study of three aerospace grade aluminum alloys (AA2024-T351, AA5052-H32, and AA7075-T651) in multiple processing states. These processing states include: the base material, fusion welded material, FSW material, and a study of FSW post-processed fusion welds of each of the alloys. The mechanical properties studied include Vickers hardness and microhardness (in the case of AA5052), tensile strength, and corrosion resistance.

Hybrid processes would be applicable to aerospace, marine, and automotive manufacturing. It could create more complex geometries such as: landing gear, ship hulls, and automotive body framing. The addition of Friction Stir Processing (FSP) to fusion welding results in less clamping force required, and in some cases, could improve the joint quality of the material, given the use of a more rigid FSW machine that can handle the downforces and lateral forces required of friction stir welding and processing.

In the case of automotive applications, the use of a combined process could be more achievable. Parts such as door frames, could be sent through a post-weld heat treatment quite easily, as opposed to an entire aluminum ship hull. The same could be said for landing gear, or other smaller parts, used in aircraft or marine applications.

Experimental Procedure

Three materials were chosen for study for this hybrid process due to their relevance in aerospace applications; the materials chosen are: AA2025-T351, AA5052-H32, and AA7075-T651. These aluminum alloys were ordered through Kaiser Aluminum out of Spokane, WA. The batches of each material were certified as aerospace grade aluminum alloys, and their relevant properties for the specific batches purchased are shown in Tables 1-3 for AA2024-T351, Tables 4-6 for AA5052-H32, and Tables 7-9 for AA7075-T651. The fusion welding filler material, AA5356, has the chemical composition listed in Table 10, and the material properties listed in Table 11. All plate materials were bought in 304.8 mm x 914.4 mm x 6 mm sizes, and cut to 304.8 mm x 304.8 mm x 6 mm sections for welding, testing and FSW/FSP.

Table 1: AA2024-T351 Chemical Composition.[3]

Chemical Composition:						AA2024-T351						
	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	V (%)	Zr (%)	Other	Al (%)
Min.	0.00	0.00	3.80	0.30	1.20	0.00	0.00	0.00	0.00	0.00	0.05	94.65
Max.	0.50	0.50	4.90	0.90	1.80	0.10	0.25	0.15	0.05	0.05	0.15	90.65
Batch												
AA2024-T351	0.09	0.18	4.60	0.74	1.30	0.01	0.11	0.02	0.01	0.00	0.05	92.89

Table 2: AA2024-T351 Mechanical Testing Results for Batch Purchased.[3][4]

Mechanical Test Results:				AA2024-T351			
					Mechanical Properties		
Lot No.	Cast No.	Metal ID	Alloy	Spec No.	YS (Mpa)	UTS (Mpa)	Elongation (%)
Spec.				Min.	345.00	483.00	18
				Max.			
142199B9	825	1913210	2024	1	342.00	487.00	16.9
				2	345.00	488.00	16.9

Table 3: AA2024-T351 Material Properties.[4]

Relevant Material Properties:		AA2024-T351	
Vickers Hardness	Thermal Conductivity (W/mK)	Solidus (°C)	Liquidus (°C)
137	121	502	638

Table 4:AA5052-H32 Chemical Composition.[5]

Chemical Composition:					AA5052-H32					
	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	Other	Al (%)
Min.	0.00	0.00	0.00	0.00	2.20	0.15	0.00	0.00	0.05	97.60
Max.	0.25	0.40	0.10	0.10	2.80	0.35	0.10	0.05	0.15	95.70
Batch										
AA5052-H32	0.07	0.20	0.00	0.10	2.45	0.21	0.00	0.01	0.00	96.958

Table 5: AA5052-H32 Mechanical Testing Results for Batch Purchased.[5][6]

Mechanical Test Results:				AA5052-H32			
					Mechanical Properties		
Lot No.	Cast No.	Metal ID	Alloy	Spec No.	YS (Mpa)	UTS (Mpa)	Elongation (%)
Spec.				Min.	159.96	215.12	9
				Max.		262.00	
03/05/157DO	13085B45	53009038	5052	1	177.88	231.66	17
				2	177.20	233.04	15

Table 6: AA5052-H32 Material Properties.[6]

Relevant Material Properties:		AA5052-H32	
Vickers Hardness	Thermal Conductivity (W/mK)	Solidus (°C)	Liquidus (°C)
68	138	607	649

Table 7: AA7075 Chemical Composition.[6]

Chemical Composition:						AA7075-T651						
	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	V (%)	Zr (%)	Other	Al (%)
Min.	0.00	0.00	1.20	0.00	2.10	0.18	5.10	0.00	0.00	0.00	0.05	91.37
Max.	0.40	0.50	2.00	0.30	2.90	0.28	6.10	0.20	0.05	0.01	0.15	87.12
Batch												
AA7075-T651	0.07	0.17	1.50	0.06	2.40	0.19	5.50	0.03	0.01	0.01	0.05	90.01

Table 8: AA7075-T651 Mechanical Testing Results for Batch Purchased.[7][8]

Mechanical Test Results:				AA7075-T651			
					Mechanical Properties		
Lot No.	Cast No.	Metal ID	Alloy	Spec No.	YS (Mpa)	UTS (Mpa)	Elongation (%)
Spec.				Min.	503.00	572.00	11
				Max.			
135157B6	816	1906515	7075	1	505.00	578.00	12
				2	509.00	581.00	12.1

Table 9: AA7075-T651 Material Properties.[8]

Relevant Material Properties:		AA7075-T651	
Vickers Hardness	Thermal Conductivity (W/mK)	Solidus (°C)	Liquidus (°C)
175	130	477	635

Table 10: AA5356 Chemical Composition.[9]

Chemical Composition:					AA5356						
	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	Be (%)	Other	Al (%)
Min.	0.00	0.00	0.00	0.05	4.50	0.05	0.00	0.06	0.00	0.05	95.29
Max.	0.25	0.40	0.10	0.20	5.50	0.20	0.10	0.20	0.0008	0.15	92.90

Table 11: AA5356 Material Properties.[9]

Relevant Material Properties:	AA5356	
Thermal Conductivity (W/mK)	Solidus (°C)	Liquidus (°C)
117	571	635

Fusion welding for aluminum alloys 2024-T3, 5052-H32, and 7075-T651 were performed via TIG welding processes with AA5356 filler. The plates were milled to have a v-notch shape for the weld bead to fill into the full 6 mm thickness. All welds were done at 200 A for a full 152.4 mm weld, joining two 152.4 mm x 152.4 mm x 6 mm plates together for further analysis.

All friction stir welds were performed using the ABB IRB 940 and Friction Stir Link system with a specifically designed tool. The ABB robot has 6 axes of motion, and is designed for light deburring as well as pick and place type movements.[3] In addition to its impressive mobility, the IRB 940 has a vertical machining power of 12.75 kN and a horizontal machining power of 3.70 kN.[10] While these figures are impressive for deburring and pick and place movements, they cause a hindrance to the FSW/FSP technique as it requires high stiffness and large downforces. The IRB 940 has a large work envelope, which can reach 1600 mm swinging from left to right, as well as from front to back.

The Friction Stir Link system is accompanied by a specifically designed tool chosen based on the recommendations of Mishra et. al.[11] and has a scrolled shoulder with a tapered threaded pin. This design is trademarked and was purchased through MegaStir Technologies. This tool is illustrated in Figure 1, and 2, and has a 3.8 mm long tapered pin with a maximum base diameter of 4.74 mm; the shoulder has a 15 mm diameter. This FSW is made of H13 steel, and was chosen to penetrate the full weld bead of a fusion welded material. The tool is designed to rotate in a counter clockwise direction, and the tool depth of penetration within the material can vary dependent on parameters and the specific material being used.

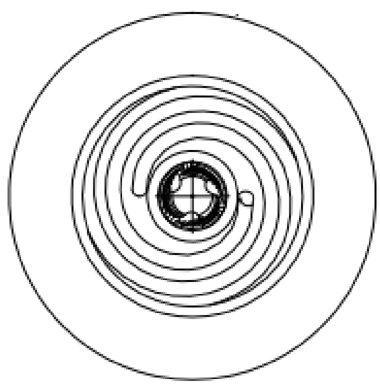

Figure 1: MegaStir FSW tool with scrolled shoulder.[12]

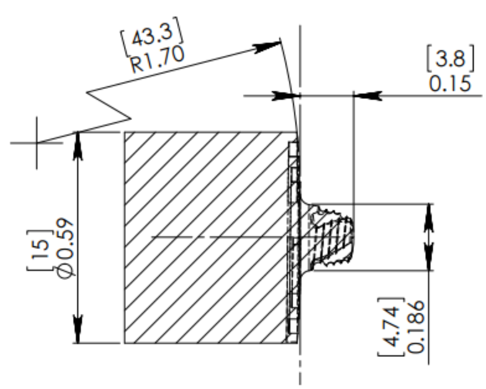

Figure 2: MegaStir FSW threaded pin tool.[12]

Clamping was done with Bessey adjustable clamps that can be set for a multitude of thicknesses, and are bolted directly to any type of table. In this case, a large steel table with pre-drilled bolt holes was used with four Bessey clamps holding down the materials being welded and processed. The clamp chosen was the Bessey 751S[13], which has a maximum clamping force of 122.8 kN.

Mechanical testing was done for Vickers hardness on AA2024-T351 and AA7075-T651, while microhardness testing was performed on AA5052-H32. The microhardness testing was chosen because of the relative softness of the base material. This material was also tested with Vickers hardness. A difference of 0.26% between Vickers hardness and microhardness styles of testing was found for the base material, tested over 200 data points.

Tensile testing was done with mini tensile samples that sustain a gauge length of 1 mm x 1 mm x 3 mm.[14] This tensile specimen has a simplified contact area and can be replicated to exact specifications easily by cutting with a high precision cutting device such as a wire EDM. This design also eliminates the pin holes from some of the other previously used mini tensile specimens. There is limitation to the effectiveness of the mini-tensile specimen for materials with larger grain sizes, as the larger the grain, the more likely the tensile sample is to break prematurely, due to the small gauge length dimensions. This effect proved to be true for base material specimens of AA2024 and AA7075 alloys chosen for this hybrid process analysis, but the grain size for the fusion welded and friction stir welded alloys was sufficiently low to create more accurate results. An extensometer was not used with the mini tensile samples, and therefore, the tensile data collected is used as a comparison study between the various processing states of the aluminum alloys.

Corrosion testing for all aluminum specimens was carried out using ASTM G110-92 (2015), which is an immersion type corrosion test using NaCl and hydrogen peroxide (H2O2). This test is primarily used for heat-treatable aluminum alloys but can be used for other alloys as well. This immersion corrosion test was developed to identify differences in the effects of other thermal processes on an alloy of material originating in a certain temper.[15] The specimens must be cleaned using an etching cleaner consisting of distilled water, nitric acid and hydrofluoric acid. The specimens must be cleaned in the etching solution for 1 minute at 93^{o}C, and then placed in concentrated nitric acid for one minute more. After this, the material can be transferred to the test vessel for immersion. For this test, pint sized tempered glass jars were used to separate the samples, and also provide a closed environment for the test. The cleaned samples were submersed in the solution of salt and hydrogen peroxide for 24 hours and then pulled out, rinsed in distilled water, and then air dried.[15]

Fusion welding for aluminum alloys 2024-T3, 5052-H32, and 7075-T651 were performed via TIG welding processes with AA5356 filler. The plates were milled to have a v-notch shape for the weld bead to fill into the full 0.25” thickness, shown in Figure 3.10. All welds were done at 200 A, for a full 6” weld, joining two 6” x 6” x 0.25” plates together for further analysis.

All friction stir welds were performed using the ABB IRB 940 and Friction Stir Link system with the scrolled shoulder, and tapered threaded pin tool designed by MegaStir.

The friction stir welding of the base material plates was based off of the parameter testing for AA2024-T351, and then modified for the differing solidus temperatures and thermal conductivity values of the other alloys (AA5052-H32 and AA7075-T651). The FSW parameters chosen are summarized in Table 12.

Table 12: FSW parameters for base materials.

Material	Plunge Stage		Traversing Stage	
	RPM	Linear Speed (mm/min)	RPM	Linear Speed (mm/min)
AA2024-T351	1500	15	900	30
AA5052-H32	3000	15	3000	30
AA7075-T651	3000	15	2500	30

The friction stir processing of the fusion welded joints took on much the same philosophy as the friction stir welding of the base material plates. The only difference is the added material of AA5356-O filler for the fusion welded sections, on which the top of the weld bead is ground down before processing. This filler material has a much higher melting point than the alloys, and the thermal conductivity is greater than all three aluminum alloys studied. Due to these differences, the rotational and traversing parameters changed for all but the AA5052-H32 materials. The parameters used for FSP of the FW zones is summarized in Table 13.

Table 13: FSP parameters for processing of FW zones.

Material	Plunge Stage		Traversing Stage	
	RPM	Linear Speed (mm/min)	RPM	Linear Speed (mm/min)
AA2024-T351	1500	15	900	30
AA5052-H32	3000	15	3000	30
AA7075-T651	3000	15	3000	30

Results and Discussion

The study of the effects of fusion welding, friction stir welding and the hybridization of the process on AA2024-T351 was studied and compared to the FSW of AA2024. There is no general comparison for the fusion welding of AA2024-T351 as it is a non-weldable material. It can also be noted that no fusion welded samples could be cut for tensile testing. The joints created with fusion welding crumbled when cutting with EDM due to the significant amount of cracking within the structure.

For this aerospace grade aluminum alloy, AA2024-T351, the FSW surpasses the average values of the fusion weld in each section out from the weld center. The friction stir processed fusion weld has hardness values much below the friction stir weld and the fusion weld as it stirs the material in the weld zone for a more homogenous joint. The fusion weld zone has the highest thermomechanically affected zone (TMAZ) hardness values at only 7.4% lower than the base material (BM). The heat affected zone (HAZ) of the FSW has the highest hardness values at only 10.8% lower than the BM, and the stir zone (SZ) of the friction stir processed fusion weld is higher than the friction stir welded material at 31.4% lower than the BM. In some areas, the FSW is only 4% lower than the BM. The FSP over the FW is an average of 35% lower than the BM. The microhardness values are summarized in Figure 3.

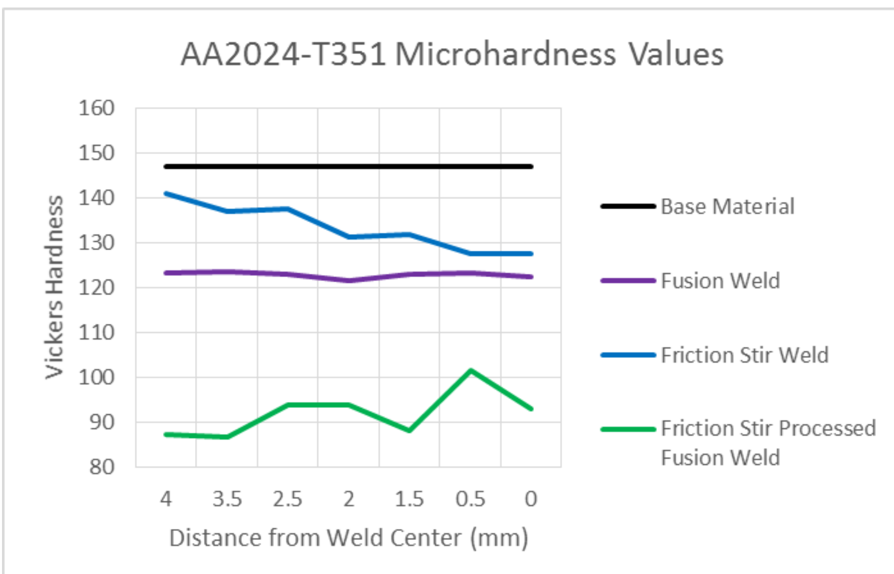

Figure 3: Vickers microhardness values for AA2024-T351 in four processing states.

A summary of the Vickers hardness values is given in Table 14. This yields an insight into how the material evolves with the addition of the extra process, and how it differs from the FSW material. The material was studied for microhardness values 30 days after processing for both the fusion weld and the friction stir welded samples. Therefore, the hardness values could have changed due to natural aging over this time.

Table 14: Summary of Vickers microhardness data for AA2024-T351 in four processing states.

BASE MATERIAL		FUSION WELDED MATERIAL			FRICTION STIR WELDED MATERIAL			FUSION WELDED + FRICTION STIR WELDED MATERIAL		
BM	146.927	BM	146.927	% Below BM	BM	146.927	% Below BM	BM	146.927	% Below BM
		HAZ	117.969	19.71%	HAZ	131.016	10.83%	HAZ	N/A	N/A
		TMAZ	136.011	7.43%	TMAZ	120.938	17.69%	TMAZ	90.529	38.39%
		Weld Bead	94.872	35.43%	Weld Bead	N/A	N/A	Weld Bead	59.929	59.21%
		SZ	N/A	N/A	SZ	99.977	31.95%	SZ	100.762	31.42%

The friction stir processing of the fusion weld yielded a much lower ultimate tensile strength (UTS) than the FSW material. It would be interesting to compare this to the fusion welded material, but due to cracking within the material, samples for tensile testing were not able to be extracted from the fusion welded material, making its UTS value zero. The tensile strength comparison is illustrated in Figure 4.

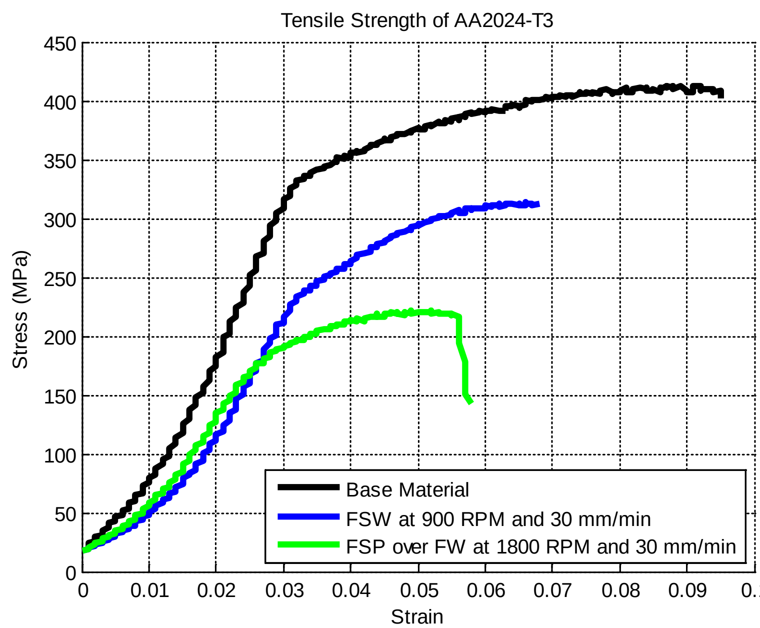

Figure 4: Tensile strength comparison of AA2024-T351.

It can be noted that the base material value for mini-tensile testing is 13.6% below that of the ASM data value for the UTS of AA2024-T351. This value, at 417.5 MPa, as compared to the ASM value of 483 MPa, could be largely due to the small gauge length of the miniature tensile samples cut. The average grain size of the base material was found to be 221.3 μm, which only gives the ratio of the grain size to the gauge length of 1000 μm to be 1:5. Since the material is rolled, the grains are longer in one direction than the other. When fusion welding occurs, the melting of the material decreases the grain size to create a ratio of 3:100 between the respective grain size of the material and the gauge length, which is much smaller than the original base material. The friction stir welded material yields yet smaller grains than the fusion welded material.

The tensile data from the friction stir welded material was found to be 32.4% lower than the ASM standard for the base material at 326.4 MPa, which is 21.8% lower than the base material value achieved with the ADMET mini-tensile tester. The hybrid process, of the friction stir processed fusion weld, yielded a tensile strength of 248.3 MPa, which is 48.5% lower than the ASM standard, and 40.5% lower than the base material tested with the ADMET system.

The corrosion testing of AA2024 showed a good amount of intergranular corrosion for the base material, which was not seen in the FSW or FSP of the FW states. The fusion weld itself yielded pitting and exfoliation corrosion. Imaging of the corrosion impact on the substrate is given in Figures 5 and 6.

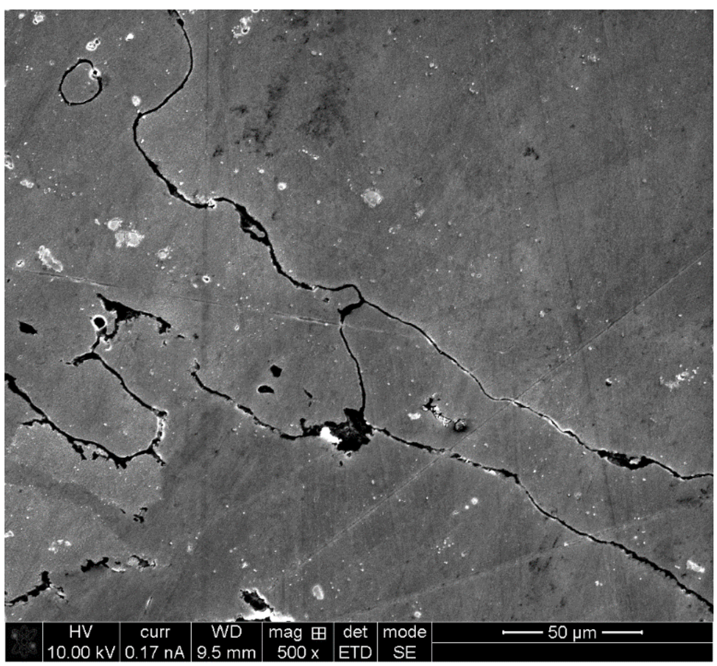

Figure 5: AA2024-T351 base material intergranular corrosion at 500X.

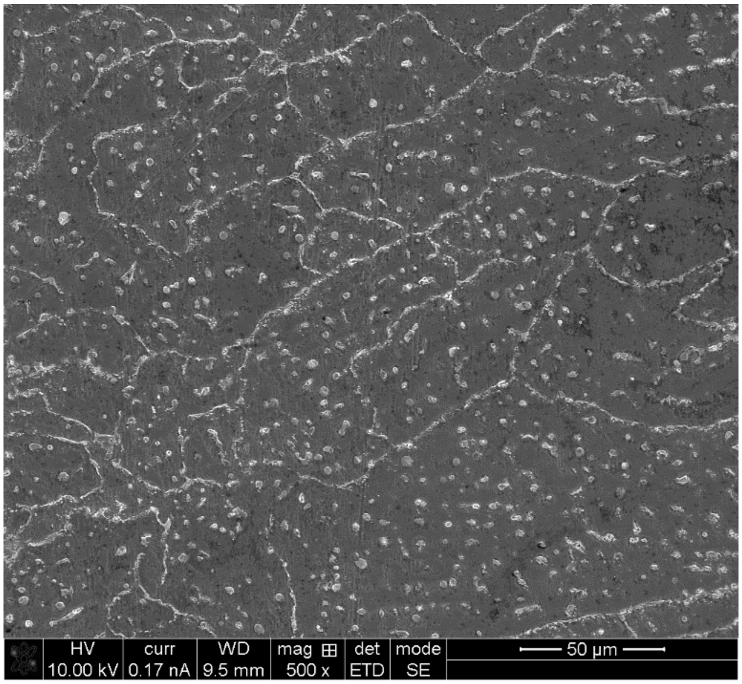

Figure 6: AA2024-T351 FW pitting corrosion at 500X.

The varying processing states of AA5052-H32 provided for interesting results when comparing the four different processing states. AA5052-H32 is considered to be a weldable material, so therefore the fusion between the weld bead and the material should provide for a sturdy connection between the two materials.

This aerospace grade alloy has a FW that has hardness values above the FSW and FSP, over FW zones, in each section out from the weld center. The friction stir processed fusion weld is comparable to the friction stir welded joint, in hardness values, along the SZ, HAZ, and TMAZ. The TMAZ is hardest in the friction stir processed fusion weld at 22.6% lower than the BM, while the HAZ is hardest for the fusion welded material at 10.41% lower than the BM. The SZ, however, is hardest in the FSW material at 18.4% below the BM. The microhardness values are summarized in Figure 7.

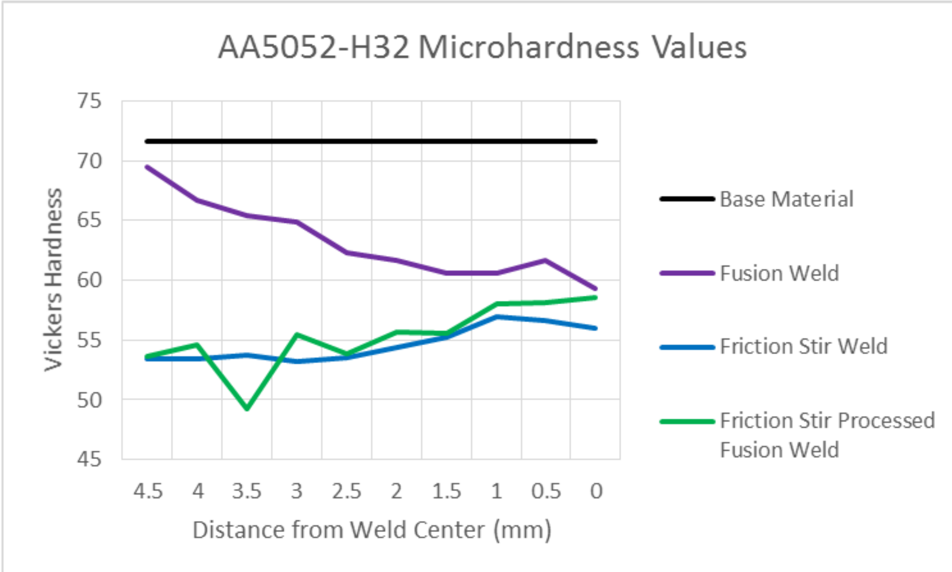

Figure 7: AA5052-H32 Vickers microhardness values for four processing states.

A summary of the Vickers hardness values is given in Table 15, and yields an insight into how the material evolves with the addition of the extra process, and how it differs from the FSW material.

Table 15: Summary of Vickers microhardness data for AA5052-H32 in four processing states.

BASE MATERIAL		FUSION WELDED MATERIAL			FRICTION STIR WELDED MATERIAL			FUSION WELDED + FRICTION STIR WELDED MATERIAL		
BM	71.628	BM	70.447	% Below BM	BM	71.628	% Below BM	BM	71.628	% Below BM
		HAZ	63.113	10.41%	HAZ	53.133	25.82%	HAZ	53.648	25.10%
		TMAZ	54.313	25.57%	TMAZ	54.576	23.81%	TMAZ	55.435	22.61%
		Weld Bead	77.750	-10.37%	Weld Bead	N/A	N/A	Weld Bead	N/A	N/A
		SZ	N/A	N/A	SZ	58.461	18.38%	SZ	58.189	18.76%

The tensile testing of the four processing states are illustrated in Figure 8. The friction stir processing of the fusion weld yielded a higher tensile strength than the FSW. The base material has a lower UTS than the fusion welded material, due to the filler metal within the joint. The base material value for AA5052-H32 is 3% above the specification by ASM (228 MPa), at 235.15 MPa. The grain size of the non-heat treatable alloy is smaller than that of AA2024-T351 and AA7075-T651, therefore providing the ADMET tensile test valid for this material. The fusion welded material provided a higher UTS at 266.8 MPa, 17% higher than the ASM standard for the alloy due to the AA5356 filler material within the joint. The friction stir welded material is 39.9% lower than the ASM standard for the base material of AA5052-H32 at 137 MPa. The higher UTS of the friction stir processed fusion weld is 14.8% lower than the base material specification at 194.2 MPa.

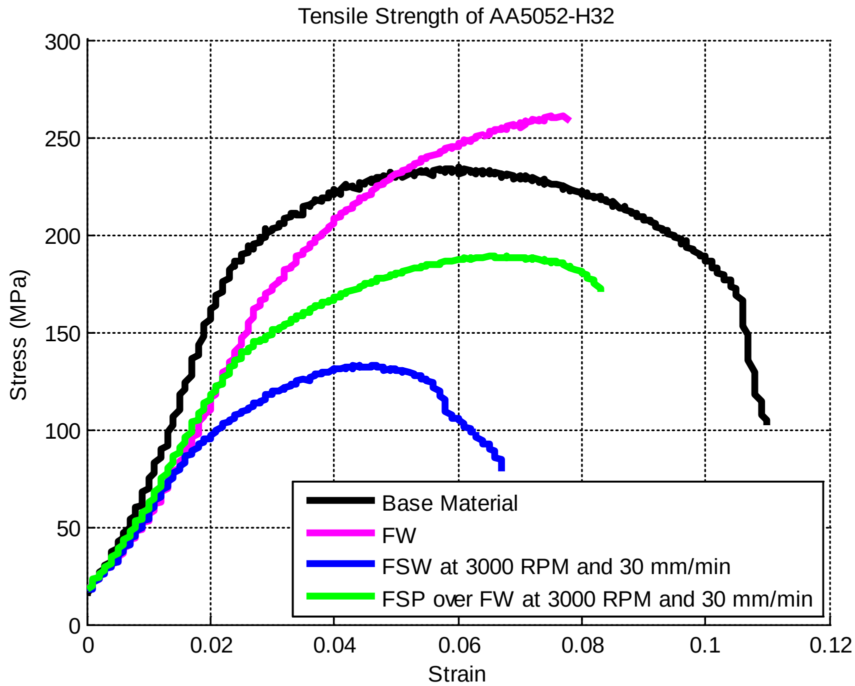

Figure 8: Tensile strength comparison of AA5052-H32.

The corrosion testing of AA5052 did not show much intergranular corrosion for the base material, as well as the fusion weld, or either of the FSW/FSP states. There was pitting and some exfoliation corrosion on all four processing states. The representing corrosion for the hybrid process for AA5052 is shown in Figures 9 and 10.

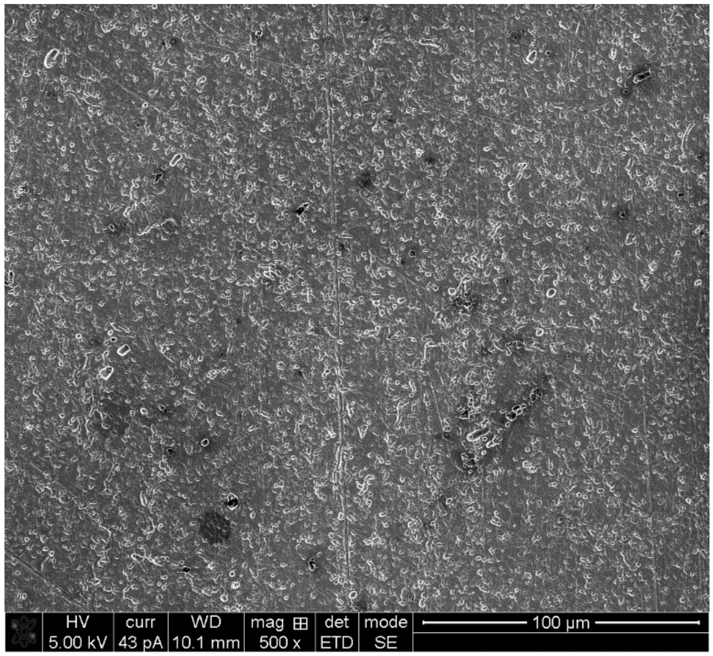

Figure 9: Pitting corrosion found in AA5052-H32 base material at 500X.

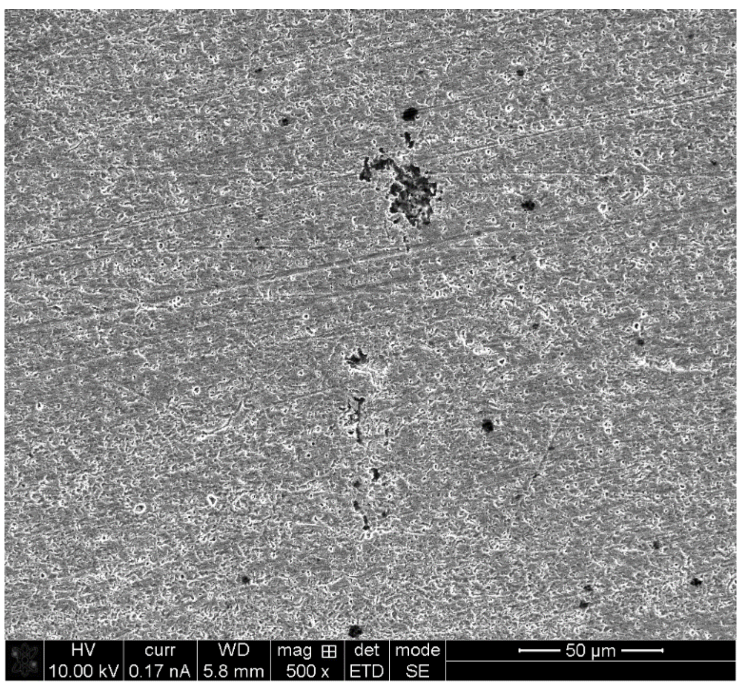

Figure 10: Pitting and exfoliation corrosion in FSP fusion weld of AA5052-H32.

Aluminum alloy 7075 is an un-weldable alloy in any state of heat treatment. The weld bead solidified quickly, but no evidence of liquation crack was found, as was seen with AA2024-T351.   For this aerospace grade alloy, the fusion weld has higher hardness values than the friction stir welded and friction stir processed fusion welds. None of the processing states come close to the base material hardness values.

All three of the processed states have the highest average hardness values closest to the weld center, and up to 1.0 mm away from the centerline. The fusion welded material has the highest HAZ hardness values at 17% lower than the base material values. The friction stir processed fusion weld has the highest TMAZ and SZ hardness values, as compared to the friction stir welded material, at 37.5% and 35.3% lower than the base material, respectively. Even though the friction stir welded material has higher overall hardness, the transition between affected zones is smooth, as compared to the friction stir welded material. The microhardness values across the four processing states are summarized in Figure 11. The comparison of Vickers hardness values for all four processing states is given in Table 16.

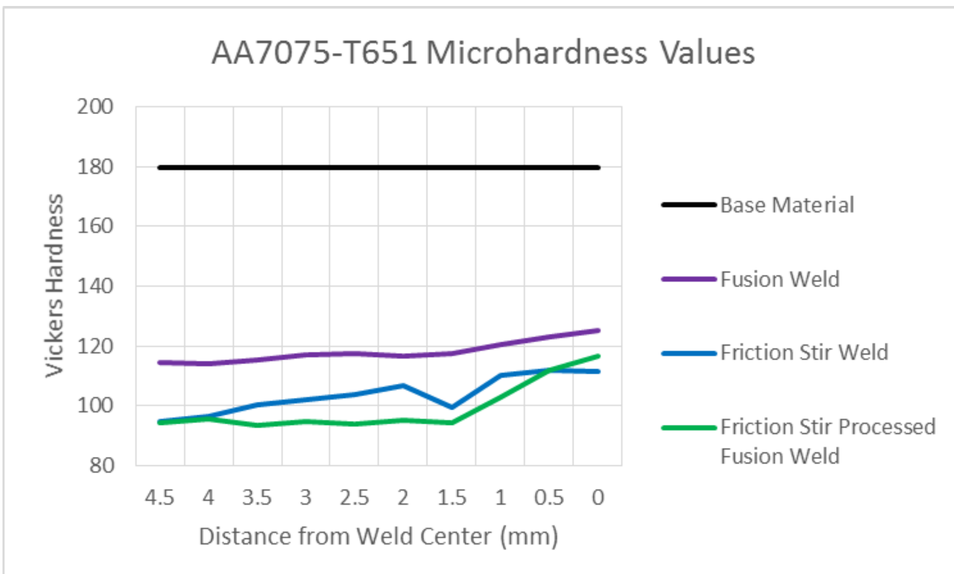

Figure 11: Vickers microhardness values for AA7075-T651 in 4 processing states.

Table 16: Summary of Vickers microhardness data for AA7075-T651 in four processing states.

BASE MATERIAL		FUSION WELDED MATERIAL			FRICTION STIR WELDED MATERIAL			FUSION WELDED + FRICTION STIR WELDED MATERIAL		
BM	179.53	BM	179.53	% Below BM	BM	179.53	% Below BM	BM	179.53	% Below BM
		HAZ	149.0067	17.00%	HAZ	94.76924	47.21%	HAZ	97.63172	45.62%
		TMAZ	110.4128	38.50%	TMAZ	106.8876	40.46%	TMAZ	112.1011	37.56%
		Weld Bead	109.2813	39.13%	Weld Bead	N/A	N/A	Weld Bead	68.52426	61.83%
		SZ	N/A	N/A	SZ	115.704	35.55%	SZ	116.0986	35.33%

The tensile testing of the four processing states provided for more insight into the introduction of a hybrid process for the manufacturing of parts. It can be noted that the base material was found to have a UTS of 456.4 MPa, which is 20.2% lower than the ASM standard for AA7075-T651 at 572 MPa. This lowered value, as compared to the standard, could be due to the small gauge length of the miniature tensile samples cut. The average grain size of the base material was found to be 513.7 μm. This gives the ratio of the grain size to the gauge length of 1000 μm to be approximately 1:2. Since the material is rolled, the grains are longer in one direction than the other. When fusion welding occurs, the melting of the material decreases the grain size to create a ratio of 75:1000, which is significantly smaller than the original base material. The friction stir welded material yields even smaller grain size than this FW material. The results are gathered in Figure 12.

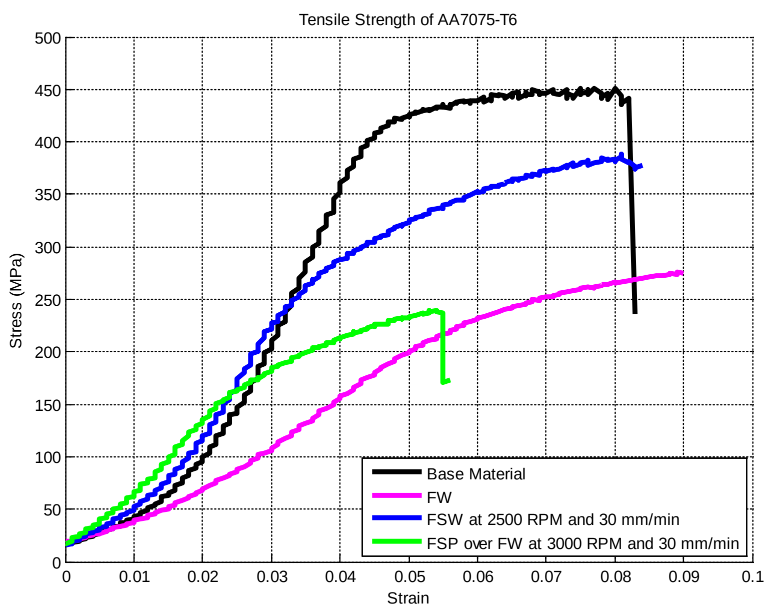

Figure 12: Tensile strength of AA7075-T651 in four processing states.

The UTS of the fusion welded material, at 278.14 MPa, was found to be 51.3% lower than the ASM standard, and 39% lower than the ADMET tested base material. The tensile data from the friction stir welded material was found to be 398.2 MPa, 30.3% lower than the ASM standard, and 14.7% lower than the ADMET tested base material. The tensile data for the hybrid process of friction stir processed fusion welding of AA7075-T651 yielded results between that of the fusion weld and friction stir weld tensile strength. The UTS was found to be 270.8 MPa, 52.6% lower than the ASM standard, and 40.7% lower than the ADMET tested base material.

The corrosion testing of AA7075 showed some intergranular corrosion, as well as some exfoliation corrosion and pitting, for the base material. Some intergranular corrosion was found in the fusion weld, as well as a large amount of pitting in the weld bead. This intergranular corrosion was also found in the TMAZ of the FSW. Pitting and exfoliation corrosion was found in the FSP fusion weld. The extent of the corrosion is seen in Figures 13 and 14.

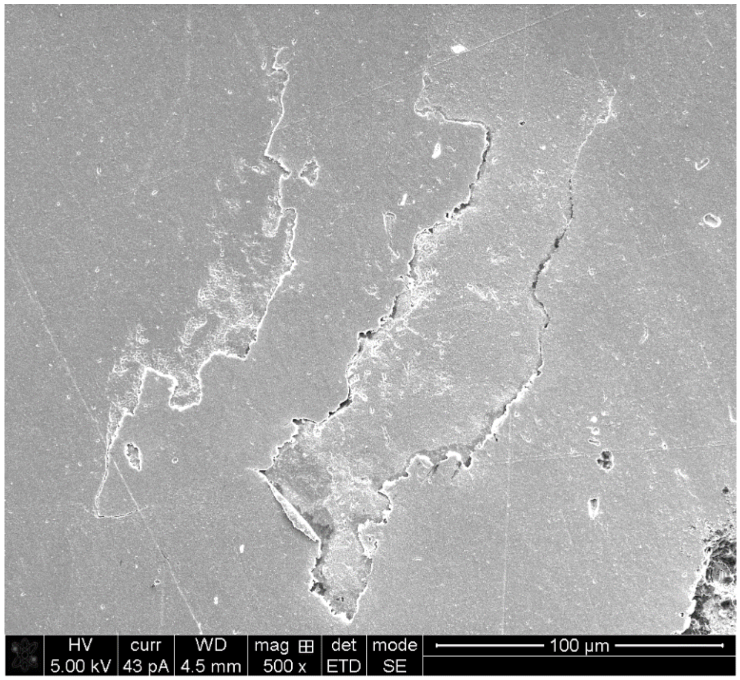

Figure 13: Intergranular corrosion of AA7075-T651 base material at 500X.

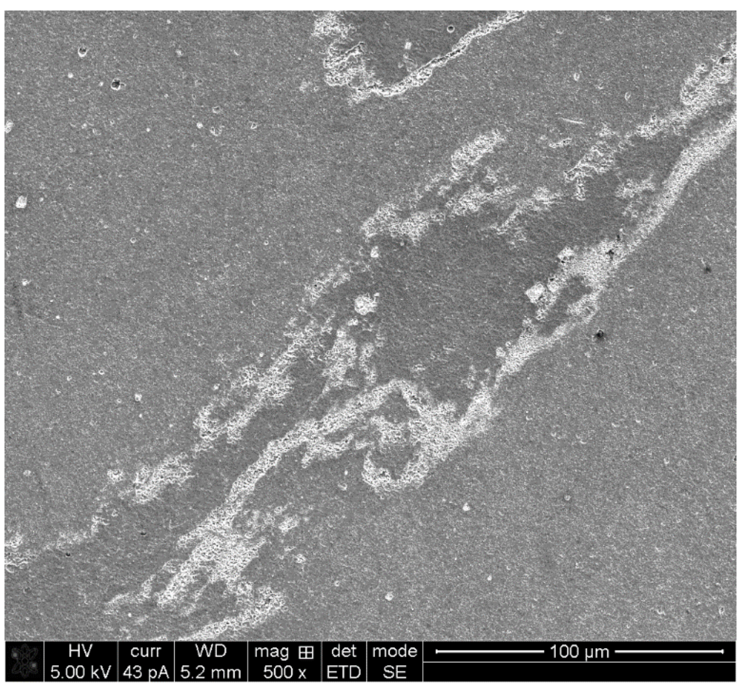

Figure 14: Exfoliation corrosion of AA7075-T651 FSP fusion weld at 500X.

Conclusions

Although the hybridization of fusion welding and friction stir welding is not a new technology, the introduction of this processing combination is new for aerospace grade aluminum alloys. The materials previously studied: AA2219, AA5083-H321, AA6082-T6, SS304L, and SS400, are all weldable aluminum and stainless steel alloys.[16-23] The analysis of the hybrid process done in the embodiment of this research incorporates the weldable aerospace grade AA5052-H32 alloy, and non-weldable aerospace grade alloys: AA2024-T351 and AA7075-T651. The study of FSP of fusion welds, in the past, has focused mainly on the surface processing of the fusion welds. This research studies the friction stir processing of the entirety of the weld nugget within the joint, creating a more homogenous mixture, as a traditional friction stir weld joining process would do. The processing of the entire joint creates a better opportunity for non-weldable alloys to use this hybrid process.

From the analysis of the three aerospace grade aluminum alloys, the introduction of a hybrid process for manufacturing is plausible, dependent on the application of the final product. The three differing aerospace grade aluminum alloys provide different results, as to the effectiveness of this technology, using the ABB IRB 940 robot. Given a more robust robotic platform, the plausibility for the hybrid technology of combining fusion welding and friction stir processing could increase, given the addition of variable downforce and rigidity of the robotic structure. This added stability would provide for a possibility to decrease the temperature at which the materials are friction stir welded, which in turn would decrease the effects of heat on the TMAZ and HAZ surrounding the friction stir welded/processed joint.

In general, FSW produces material properties that are 70-98% of the original base material properties, and when the hybrid process of combining fusion welding with FSP is compared to FSW alone, the results show that the process entirely plausible for manufacturing. However, the friction stir welding of the base material alone is preferable due to the higher material properties. In the case of difficult geometries, or the inability to clamp the material properly, a hybrid process that combines fusion welding and friction stir processing can be substituted for AA2024-T351, provided that the final material properties are within the acceptable range for the specific application. Given a more robust FSW robot or machine, the material properties could be greatly improved by dropping the joining temperature. The corrosion resistance of the friction stir weld, compared to the friction stir processed fusion weld, has negligible differences with pitting and some intergranular corrosion. The two processes, by view of corrosion resistance, are interchangeable. Natural aging may require the use of post-weld heat treatments for this heat-treatable alloy, to maintain acceptable material properties for the longevity of the application.

For AA5052-H32, the mechanical property values of the hybrid process, as compared to the base material, fall within the acceptable range for friction stir welded materials. Compared to friction stir welding, the hardness values are almost identical. The tensile strength is improved over friction stir welding with this particular robotic setup. This is largely due to the weld bead mixing with the base material. This mixing creates a homogenous mixture that is stronger in tensile strength that the original material in the FSW processing state. Therefore, it can be concluded that the hybrid process is a viable option for AA5052-H32. The fusion weld may provide for a higher UTS, but the ductility of the material would be greatly reduced, as suggested by the tensile data. The corrosion resistance of this alloy does not vary significantly with the hybrid processing state, as compared to the friction stir welded state. Because AA5052 is a non-heat treatable alloy and is cold worked to get to the H32 state, this material does not experience natural aging and would not require the use of post-weld processes, given that the weld achieves the desired property specifications.

The use of a hybrid process with AA7075-T651 is less plausible than the use of friction stir processing, with fusion welding for AA2024 and AA5052, due to the decreased hardness and tensile values. The combination of fusion welding and friction stir processing does provide for an increase in hardness over the friction stir welded material, but only by a small amount for this robotic setup. The tensile results however, provide that the hybrid process is much less effective than the friction stir welding process alone. A post-weld heat treatment could change these results, provided that the part has difficult geometries. These configurations would require the use of combining processes, because of difficult geometries that do not allow for proper clamping. Natural aging may require the use of post-weld heat treatments for this heat-treatable alloy, to maintain acceptable material properties for the longevity of the application regardless of processing state. Once again, the corrosion resistance of the material is improved by friction stir welding, and the friction stir processed fusion weld is relatively the same, when it comes to corrosive properties for this material.

Future Work

It is recommended that future work be done studying spot welding using fusion welding techniques, and post-processing with friction stir welding, in order to shorten the joining process of the hybrid technique. This would also reduce the incidence of the introduction of a new material to the joint. It would also be plausible to study part building with FSW, given a stiffer robotic structure using complex angles, shapes, and curvatures. Using robotic friction stir processing of fusion welds at complex angles could provide for a more additive manufacturing approach to creating larger complex parts.

Due to the large HAZ found in all of the materials after fusion welding, it is proposed that the use of laser welding or electron beam welding be studied with the hybrid process to decrease the thermomechanical effects on the materials. These modern fusion welding techniques could provide for better overall material properties outside of the weld zone and the friction stir processed stir zone.

Since the addition of AA5356 filler adds a different alloy in the joint between all three materials, it might also be prudent to study different filler materials for AA2024-T351 and AA7075-T651 for fusion welding as the compositions might match the alloys more readily. As it stands, the addition of the different alloy between the base plates might make for different composition as compared to the ASM specification for the aerospace grade alloys, hence rendering outside the acceptable material specifications for composition.

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