**Development of Hybrid Manufacturing Technology for
Net-Shape Production of Monolithic Structures**

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By

Mohamed Aly

Dr. Ahmed Sherif El-Gizawy, Thesis Supervisor

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**Development of Hybrid Manufacturing Technology for
Net-Shape Production of Monolithic Structures**

Presented by

Mohamed Aly,

A candidate for the degree of

Master of Science

and here by certify that, in their opinion, it is worthy of acceptance.

Professor Sherif El-Gizawy

Associate Professor Matt Maschmann

Professor Hani Salim

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ABSTRACT

The present work aims at exploring a new processing approach, ‘Hybrid Manufacturing (HM)’ technology for net-shape production of monolithic structures for the transportation industry. The HM process combines friction stir welding (FSW) and forming in order to modify the properties of the preform to better meet design requirements and provide net-shape products. This paper focuses on understanding the process behavior and the effects of various process parameters on the properties and integrity of the produced monolithic structure during production. Formability of the produced monolithic structures is evaluated through stretch forming process experiments. The results obtained offer an understanding of the effects of the important process parameters needed to produce quality monolithic structures that fulfill design requirements and service conditions

CHAPTER 1: INTRODUCTION

This research aims at exploring a new processing approach, ‘Hybrid Manufacturing (HM)’, for net-shape production of monolithic structures for the transportation industry. The HM technology combines friction stir welding (FSW) and sheet metal forming in order to optimize the properties of the preform to better meet design requirements and provide net-shape products. HM can provide several advantages, reduced weight, part count reduction, improved damage tolerance, improved material and energy utilization, and cost savings¹⁻³. The current work focuses on understanding the effects of various parameters on the properties and integrity of a structure produced using the HM processing approach.

1.1 Statement of Problem

There is little information available about the potentials and applications of the proposed approach. The effects of different FSW process designs on performance and formability of the preforms needs to be investigated. Properties and process-induced defects evolved during HM need to be characterized and managed using parametric investigation techniques. The present work focuses on exploratory and advanced development of HM for manufacturing large monolithic parts fabricated out of 2xxx and 7xxx series of aluminum alloys. It addresses material characterization, process-induced damage, process verification and identification of transition pathways. The proposed investigation will provide capability for robust processes, prediction and characterization of process-induced damage, and properties of the finished structure.

CHAPTER 2: LITERATURE REVIEW

2.1 FRICTION STIRE WELDING

Friction stir Welding is a rather new technique, initially developed in 1991 by The Welding Institute (TWI) in Cambridge, England⁴ and has gradually grown in popularity since then. While many techniques exist for joining materials, the advantages of Friction Stir Welding is its ability to join dissimilar metals⁴ and that there is no phase change as witnessed by other welding techniques, with microstructural changes in the welded part as FSW involves no melting for the joining process.

Friction stir welding uses localized plastic deformation at the interface of the joint for establishing a bond between the base metals, shown in Figure 2.1. In the FSW process, the tool rotates and generates heat via interface friction and causes plastic deformation by extrusion at the joint interface⁴⁻⁷. Unlike the commonly used fusion welding processes, the interface temperature during FSW always stays below the melting point of the base metals⁸. No liquid phase transformation takes place in FSW. This makes FSW a superior choice compared to other welding procedures that cause unfavorable microstructures and properties associated with solidification mechanisms in fusion welding. Furthermore, FSW operations have many other unique advantages: controlled properties, improved energy utilization, and is an environmentally clean process⁵⁻⁷.

Friction Stir Welding is a good candidate for HM of monolithic structures because of its capability to weld alloys that are not typically weldable using traditional joining processes. This

increased scope of joinable materials reduces restrictions on materials, which leads to an improved final product.

2.2 Process Parameters

FSW involves four stages: plunge stage (the rotating tool is plunged vertically into the joint); dwell stage (tool is held in the plunging position while still rotating); welding stage (rotating tool travels along the joint at a constant velocity); and pulling tool out stage (tool is pulled out of the joint leaving behind an exit hole). The parameters that influence the performance of FSW are displayed in Figure 2.1. They include tool rotational speed, travel speed of the tool, plunge force, plunge depth, and tool design⁵⁻¹⁶. These parameters affect the thermal and mechanical properties evolved during FSW. Numerous studies have examined FSW over a wide range of dissimilar materials¹⁵⁻²². Cavaliere et al¹⁶⁻¹⁷ investigated the mechanical and micro-structural properties of 2024-T3 and 7075-T6 aluminum sheets. Fatigue and stress analysis was performed using a weld velocity of 2.67mm/s, however, the rotational velocity was not disclosed¹⁶. The compressive flow behavior was also studied for the FSW of Al 2024-T3 and Al 7075-T735¹⁵. No information on other welding parameters or the orientations of the alloys has been given.

The two sides of the resulting weld are sometimes asymmetrical, as the result of the tool rotating around itself in a singular direction, creating an advancing side as shown in Figure 2.1 where direction of tool rotation is the same as that of welding, as well as a retreating side where . The differences between the two sides may have different structural properties as a consequence⁸.

As the plunge depth results in longitudinal pressure applied by the tool, causes frictional heat on the surface, affecting the weld quality. With extra pressure possibly leading to overheating or

extensively damaging the microstructure and low pressure being insufficient for enough plasticity to occur leading to a weakened weld.

Figure 2.1 Friction Stir Welding Process

Tool rotational speed, travel speed of the tool (welding speed), plunge force, plunge depth, and tool design, are the controlling parameters of the friction stir welding process. These parameters affect the evolved mechanical properties and process-induced damage in the course of the process. The effects of process parameters on the formability of friction stir welded blanks are yet to be determined.

The tool design affects the heat generation, the power required to weld, plastic flow and how uniform the welded joint is. There are two tool surfaces that are required to perform the heating and joining processes. The majority of the heat generated occurs in the shoulder surface if thin

plates are being dealt with, otherwise however it is the probe surface where the most of the heat is generated. The used tool in the experimental investigation was provided by Boeing Co.

Ductility is an important characteristic in the final product, however, not much research has been conducted on the ductility of friction stir welds. These limitations are addressed in the proposed work using experimental modeling to include all control and uncontrolled (noise) parameters of the FSW process. The results will lead to process conditions that help in identifying process windows for reaching specific properties suitable for the forming stage of HM. Most recently, El-Gizawy et al³ developed a combined numerical and experimental approach for controlling process-induced properties in FSW processes. The numerical component in their approach uses a non-linear finite element method to describe thermal and deformation changes along the joint in FSW. The results obtained on Al 2024-T3 sheets, offer insights into the effects of the major process parameters in processing Al 2024-T3. They help in establishing successful FSW joints that satisfy further processing requirements for Al 2024-T3 sheet service conditions. However, El-Gizawy's results were limited to cases where only similar metals of Al 2024-T3 sheets are considered. In the present work, El-Gizawy's approach³ will be extended to cases where dissimilar metals will be investigated. Furthermore, formability of the friction stir welded structure by stretch forming will be evaluated for net-shape production of monolithic structures.

2.3 STRETCH FORMING

Sheet metal forming is one of the fundamental processes of metalworking. It is utilized by the transportation industry to meet strength and durability needed for their products. The process is costly and labor intensive, requiring the mechanical joining of forged or casted components.

Stretch forming is a forming process wherein a sheet of metal is stretched and simultaneously bent over to form a large contoured part. A diagram of sketch forming process is shown in Figure 2.2.

Figure 2.2 Stretch forming processes (a) stretch forming, (b) stretch drawing, and (c) embossing²⁴

2.4 Formability of Welded Preforms

The orientation of the weld line drastically affects the material flow and formability²⁵. Due to the differences in the sheet thickness and property between blanks of joints with dissimilar materials, the welded preform may not deform uniformly during further forming operations. Chan et al²⁵ evaluated formability based on three measures: failure mode, forming limit diagram, and minimum major strain. Their results reveal that the larger gage mismatch of a welded preform, the lower the formability of welded structure.

CHAPTER 3: EXPERIMENTAL INVESTIGATIONS

Experimental investigation of the presented HM technology for production of monolithic aerospace structures was systematically planned and conducted. The objectives here is to build a knowledge base of the HM process for high strength aluminum alloys used in aerospace industry.

3.1 Materials

Boeing Co. in the United States provided the investigated materials in the present study. They include Al-Zn alloy (7075-T6) and Al-Cu alloy (2024-T3). The combination of lightweight and high strength makes the Al 7075-T6 suitable for structural aircraft parts, while Al 2024-T3 has better formability and corrosion resistance than Al 7075-T6 alloy Chemical Composition of the alloys is shown in table 3.1 and table 3.2.

Table 3.1 Major Chemical Composition % of Al 7075-T6

Al	Cu	Mg	Zn	Cr	Mn	Si	Fe	Ti
Bal.	1.2-2.0	2.1-2.9	5.1-6.1	0.18-0.28	0.3	0.4	0.5	0.2

Table 3.2 Major Chemical Composition % of Al 2024-T3

Al	Cu	Mg	Zn	Gr	Mn	Si	Fe	Ti
Bal.	3.8-4.8	1.2-1.8	0.25	0.1	0.3-0.9	0.5	0.5	0.15

3.2 The Material properties

Properties of Al 7075-T6 and Al 2024-T3 were evaluated experimentally prior to processing them. The ASTM standard²⁶ tensile test specimens used were machined from a 2mm thick sheet. They were designed to measure the stress and strain with oneinch gage length, the dimensions are shown below in figure 3.1

Figure 3.1 ASTM Standard tensile test specimen

Uniaxial experiments were done using an MTS servo hydraulic universal testing machine. It was controlled by a 45.20 MicroConsol and a 41.9 MicroProfiler, used to program the strain rate. A 1-inch extensometer was attached on the middle section of the specimen to have the strain measured, the specimen meanwhile was being clamped between the upper and lower grips. The MicroConsole was recording data about load, displacement and strain in real time by being connected to the Data Acquisition System (DAQ), with process software LabView. The test results for the properties of both materials is shown in Table 3.3.

Table 3.3 Comparison of properties of Al 7075-T6 and 2024-T3

Property	7075-T6	2024-T3
Young's Modulus (GPa)	71.7	73.1
Poisson's Ratio	0.33	0.33
Density (kg/m ³)	2795.72	2780
Initial Yield Stress (MPa)	503	345
Ultimate Tensile Strength (MPa)	578	483
Elongation (%)	11	18
R Value	0.68	0.65
K	756.6	430.2
N	0.0782	0.2288

3.3 Experimental setup and Procedures

An adapted milling machine (Figure 3.2) was used to conduct the Friction Stir Welding processes, it has custom fixtures (Figure 3.3) that were designed by a capstone group under the supervision of Dr. El-Gizawy. These fixtures consisted of three main parts; the base plate, parallel bars and the clamps. The base is required to ensure that the aluminum sheet to be welded is sitting on a smooth surface, the base sheet needed to be able to withstand 1500lbs off force exerted by the tool bit; for this A slab of steel with 1.25” thickness capped with 0.040” titanium was chosen for the base plate, the titanium was chosen for its low head conductivity to ensure it would not bond with the aluminum and effect the experimental results³⁰. To align the aluminum sheet to be welded with the Y-axis motion, pain were placed in the base plate. The base plate was

keyed into the slots on the mill surface to align it with the table and make sure it is completely square. T-nuts were used to hold the base plate in to prevent it from shifting and ensure stability.

Figure 3.2 Adapted Milling Machine for Friction Stir Welding Process

Figure 3.3 Model of Final Design of Friction Stir Welding Fixture

The parallel bars are used to distribute the load evenly from the clamps along the aluminum sheets and constraining the work pieces from separating in case of butt joint. Because of its lightweight and to keep the bars from marring the aluminum sheets to be welded and to absorb some of the weld heat from along the x-axis, the bars were milled out of aluminum. They covered the entire length of the welding process. A large clamping area was provided with the bars; however, it did not interfere with the tool or the welding procedure. A milled lip of 0.060" thickness was milled into the bottom of the bars, in order to withstand separation force during the welding process as well as pulling some of the heat from the x-direction and evenly distributing it along the weld area instead of having the heat built up around the clamping system.

Standard issue serrated clamps with step blocks were used. The studs used to hold the clamps to the table are 0.75" grade 7b steel and thread into t-nuts in the tables' channels. All blocks were ensured to be of similar height to ensure equal forces²⁷

3.4 The Tool Bit

The tool bit (Figure 3.4) is what causes friction in the friction stir welding. Upon contacting the metal, friction is generated and the material is stirred. The tool's shoulder rotates against the substrate generating most heat required for the process, the pin on the tool is plunged into the substrate and helps in stirring the metal in the solid state. The bits showed a good working life; about 30 runs for 12" a piece working on the aluminum alloys. The tool bits were cleaned promptly after usage with sodium hydroxide to inspect their condition.

Figure 3.4 Close up of New Tool Bit

3.5 Friction Stir Welding Devices and Process

All FSW investigations were conducted on an in-house established FSW rig based on an available vertical milling machine. A special fixture was designed to firmly clamp the sheets. The fixture was also provided with a specially designed support plate.

The two aluminum sheets to be welded were faced up against each other while being clamped using the fixtures discussed beforehand. Translational, Rotational velocity were set in the milling machine. The tool, rotated is thereupon plunged into the work piece. The tool creates heat via friction until the material interface becomes plasticized. Because of the mechanical mixing and adiabatic heat within the material, the stirred material is softened without reaching the melting point. This is one of the major advantages of Friction Stir Welding over conventional welding methods. Once the work area becomes plasticized, the tool traverses along the weld line to bond the materials together. The plasticized material is subsequently deformed around the tool and placed by axial force of the tool shoulder, Material is then consolidated along the weld joint leaving a solid bond between the two pieces²⁹. Figures 3.5 displays the initial setup of FSW rig.

Figure 3.5 FSW rig with the welded sheet holding fixture

Figure 3.6 FSW rig showing the tool and process pass

3.6 Parametric Evaluation of Friction Stir Welding Process

Parametric investigation using the Taguchi Method was used as this study's Design of Experiment approach to study the effects of the control process parameters on the important quality characteristics of the FSW joints. The Taguchi Method is handy for reducing the required number of tests to have base knowledge on what are the most effective parameters²⁸.

Experiments designed to investigate control process parameters were put in order, the control process parameters included the feed rate, and rotational speed on the quality characteristic of the final result was.

3.6.1 Friction Stir Welding Similar Alloys

Friction stir welding of similar alloys made out of Al 2024-T3 was investigated under different combinations of the major FSW parameters, the tool rotational velocity and welding velocity.

The experimental log is displayed in Table 3.4. It should be mentioned that the other FSW parameters were kept constant during this investigation. Table 3.5, shows the values of these fixed parameters.

Table 3.4 Experimental Log for FSW Al 2024-T3 Welds

Sample #	Rotational Velocity (RPM)	Welding Velocity (mm/sec)
2024-1	1300	0.9
2024-2	1300	1.53
2024-3	1300	2.43
2024-4	1300	3.23
2024-5	1045	2.43
2024-6	1045	1.53
2024-7	1045	3.23
2024-8	840	1.96
2024-9	840	2.43

Table 3.5 Fixed Process Parameters for FSW

Blank Dimensions	100mm X 300mm X 2mm
Type of Weld	Butt Weld
Plunge Depth	2 mm
Plunge Time	15 seconds
Dwell Time	20 seconds

Friction stir welding of similar blanks made out of Al 7075-T6 was conducted to determine the feasible conditions that produce sound welds. Table 3.6 displays the experimental conditions that resulted in successful joints. The same fixed process parameters (Table 3.5) used for welding Al 7075-T6 joints.

Table 3.6 Process parameters for FSW of Al 7075-T6

Sample #	Rot. Vel. (RPM)	Weld Vel. (mm/sec)
7075-1	1300	0.9
7075-2	1045	3.23
7075-3	840	2.43

3.7 Friction Stir Welding Dissimilar Alloys

Effects of the major control parameters of FSW (the tool rotational velocity and welding velocity) on the formability of the welded bi-alloy preforms were experimentally evaluated (Table 3.7). The feasible process window for FSW of bi-alloy made out of Al 7075-T6 and Al 2024-T6 (Bi-A) was defined from a few tests conducted prior to establishing the experimental design needed. An orthogonal array “L9” was used to develop process contour maps relating process parameters to strength and formability of the welded bi-alloy blanks.

Table 3.7 L9 Orthogonal Array for Al 7075-T6 & Al 2024-T6

Sample #	Rotational Velocity (RPM)	Welding Velocity (mm/sec)
Bi-A 1	675	1.53
Bi-A 2	675	2.43
Bi-A 3	675	3.23
Bi-A 4	840	1.53
Bi-A 5	840	2.43
Bi-A 6	840	3.23
Bi-A 7	1045	1.53
Bi-A 8	1045	2.43
Bi-A 9	1045	3.23

3.8 Stretch Forming of FSW Preforms

Stretch forming is conducted to determine the formability of friction stir welded blanks and the effects of the HM process parameters on quality of the produced monolithic structure.

Experimentally conducted stretch forming to examine the ductility and the formability of friction stir welded blanks and determining the effects of rotation speed, weld velocity on ductility was undertaken. The tool setup for stretch forming process with die, punch blank holders are shown in Figure 3.7. The welded blank (Figure 3.8, 3.9) is tightened by bolts after being placed on the die. Blank holder is applied to prevent the blanks from being drawn in the die when it is punched by the machine, resulting in blanks stretching rather than sheet thinning of material by being drawn.

Figure 3.7 MTS Machine with Stretch Forming Fixture

Figure 3.8 Tool Set Up of Stretch Forming Process

Figure 3.9 Tailor Welded Blank Set up

The Sheets from friction stir welded blanks of Al 7075-T6 and Al 2024-T3 were stretch formed. The pieces were sheared to 2x8" size from 12x8" blanks. The prepared work piece was set on the stretch-forming die, with the center of the weld aligned with the center of the die as illustrated in Figure 3.7. The punching parameters were programmed in by the MicroProfiler. The Data Acquisition system was checked beforehand by using LABVIEW, signals from the MircroConsole were processed in real time. The load, displacement and voltage were then plotted on the monitor to help evaluate the process and identify problems.

3.9 Tensile Testing

To determine the material properties of the resulting weld, uniaxial experiments were conducted via a MTS servo-hydraulic testing machine. The machine was controlled with the same MicoConsole, MicroProfiler that were used for programming the strain rate. The specimen (Figure 3.10) was clamped between upper and lower grips (Figure 3.11) and an extensometer (Figure 3.12) was attached to the middle section for measuring of the strain.

Figure 3.10 Tensile testing specimen

The samples were initially checked for any imperfections then used, a MicroConsole connected to a Data Acquisition System through with process software LabView were used to record data in real time. The data included load, displacement and strain. The tests were conducted in room temperature. For evaluation the mechanical properties of the welded joints; standard tensile test procedures were followed. The gage dimensions of the specimens were 25.4mm (1") long and 19mm (3/4") wide and with the weld zone running across the gage length. The test speed was kept constant at 1 cm /min for the duration of the test. All results are an average of three tested samples.

Figure 3.11 Hydraulic Linear Displacement Machine with Extensometer on the clamped sample

Figure 3.12 Close up of Extensometer

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Process-induced Properties of FSW Similar Alloys

This current study has three stages. In the first stage, a systematic study with differing parameters of friction stir welding for similar alloy Al 2024-T3, followed by a study of bi-alloy material (Al-2024-T3 and AL 7075-T6) followed by stretch forming.

A universal testing machine was used to determine the mechanical properties of the weld and to investigate the effect of the process parameters mechanical properties of the weld to determine the effect of the process parameters. Tensile test was conducted with the specimens cut out of welded blank from every case study using the MTS machine and data acquisition system operated using LabVIEW. Mechanical properties like Yield Strength and Ultimate Tensile Strength of Similarar are summarized in Table 4.1.

Table 4.1 Mechanical Properties of Al 2024-T3 Welds

Sample #	Rot. Vel. (rpm)	Weld Vel. (mm/s)	% Elong	% Red. In Area	YS (MPa)	UTS (MPa)
2024-1	1300	0.90	12.37	14.58	211.52	324.28
2024-2	1300	1.54	16	12.13	319.36	437.66
2024-3	1300	2.43	10.67	5.95	313.17	407.01
2024-4	1300	3.23	6.49	9.23	301.38	429.48
2024-5	1045	2.43	18.18	17.08	309.75	406.86
2024-6	1045	1.54	11.4	7.09	330.66	445.23
2024-7	1045	3.23	8.49	8.85	314.57	424.62
2024-8	840	1.96	12.73	11.17	303.69	418.08
2024-9	840	2.43	11.18	10.03	310.56	424.73

Data in Table 4.1 represents strength and ductility measures of Al 2024-T3 joints established using different combinations of rotational velocity and welding speed. From the results shown in Table 4.1, conditions in experiment #5 (rotational velocity of 1045rpm and welding velocity of 2.43mm/sec) created the weld with the most desirable properties. It has the best combination of strength and ductility (high toughness). The results from Table 4.1 were plotted onto three-dimensional surfaces relating the effect of the rotational velocity and welding velocity to the percentage of elongation to failure of the sample. The fitted surface is displayed in Figure 4.1. The contour map for joint ductility, extracted from the surface plot, is shown in Figure 4.2. These figures indicate that rotational velocity in the range of 800 to 1100 rpm and welding velocity of 1.90-2.75 mm/s would yield acceptable joint ductility for further processing.

Figure 4.1 Surface plot of the effect of weld and rotation velocity on ductility of FSW Al 2024-T3 Welds.

Figure 4.2 Process contour map for ductility index (% elongation) of FSW Al 2024-T3 joints

4.2 Process-induced Properties of FSW Dissimilar Alloys.

Mechanical properties listed in Table 4.2 show the effect of process parameters on the quality of FSW dissimilar alloys. It can be seen that Bi-A 2 creates the weld with the highest strength. Bi-A 2 produces a weld that is 18% stronger than the weakest weld. Insufficient heat is generated with the combination of higher weld velocity and lower rotational velocity (Bi-A 3); this does not provide the ideal condition for the FSW tool to soften and stir the material. However, lower weld velocity and higher rotational velocity of the tool (Bi-A 7) leads to high friction and excessive heat generated between the tool and blanks. Process parameters used in Bi-A 2 provides the optimal condition to generate heat in order to soften and perfectly stir the material leading to a complete solid weld.

Ductility of the preform generated with conditions listed in experiment Bi-A 2 is above 12%, which is suitable for further processing with stretch forming. The high joint strength of 416 MPa of weld Bi-A 2 combined with the mentioned high ductility would give the structure excellent toughness needed for aerospace structures. Figure 4.3 displays the response surface of ductility as a function of rotational velocity and welding velocity. The process contour map generated from Figure 4.3 is presented in Figure 4.4. The results indicate that rotational velocity in the range of 1045 to 1300 rpm and welding velocity of 1.5-2.5 mm/s would yield optimum joint ductility with reasonable strength.

Table 4.2 Mechanical Properties of Al 7075-T6/Al 2024-T3 Welds

Case #	Rot. Vel. (RPM)	Weld Vel. (mm/s)	% Elong.	YS (MPa)	UTS (MPa)
Bi-A 1	1300	0.90	6.8	320	395
Bi-A 2	1300	1.54	12.3	325	416
Bi-A 3	1300	2.43	9.9	335	355
Bi-A 4	1300	3.23	7.2	315	355
Bi-A 5	1045	2.43	5.9	335	354
Bi-A 6	1045	1.54	12.5	335	360
Bi-A 7	1045	3.23	7.9	317	351
Bi-A 8	840	1.96	8.9	335	364
Bi-A 9	840	2.43	7.4	345	355

Figure 4.3 Surface plot of the effect of weld and rotation velocity on ductility of Bi-metals Al 2024-T3/Al 7075-T6 welds.

Figure 4.4 Process contour map for ductility index (% elongation) of Bi-metals Al2024-T3/Al 7075-T6 joints.

From the stress-strain curve shown in Figure 4.5, it can again be shown that Bi-A2 had the highest strength, in Figure 4.6 it is shown to have the optimal qualities of a hybrid, with higher strength than Al 2024-T3 and higher ductility than 7075-T7, showing the success of the process.

Figure 4.5 Stress-strain of different cases

The elongation presented in Table 4.2 also show that Bi-A2 has the second highest elongation of the tested welds, at 9.4%, with Bi-A6 having the highest elongation at 10.2% with both cases having comparable reduction in area.

Figure 4.6 Comparison of Stress-Strain curves of 2024, 7075 and Bi-A2

4.3 Stretch Forming of FSW Preforms

Using the MTS machine the stretch forming experiments were carried at fixed parameters on FSW bi-alloy Al 2024-T3/Al 7075-T6 structures with a constant punch velocity of 10 mm/min. The blanks are firmly clamped using the blank holder. The 'V' shaped notch in the blank holder helps to hold the blank into the groove in the die, thus preventing the blank from slipping as the punch moves in to deform the blank. The stretch forming process is continued until failure of the blank. The welded blank after the failure is shown in Figure 4.14. Final stretch blank shown in Figure 4.15.

Figure 4.7 Tailored Welded Preform before Forming

Figure 4.8 Failed Tailored Welded Preform after Stretch Bending

Figure 4.9 Welded Blank after Stretch forming

After the stretch forming process was completed, the blanks were removed to conduct post forming evaluation. The failure was observed to be due to the stress concentration rather than failure in the weld itself, showing the high quality of the weld as it stretched rather than undergo fracture.

In order to evaluate the effect of process parameters on the formability, total depth of plunge at failure for different cases (Table 4.3) was measured. All formability results correlate well with the ductility properties reported in Table 4.2. Case Bi-A 2, with the highest ductility index, shows the highest formability of all other cases. The results reveal that high rotational velocity combined with slow weld velocity in FSW of bi-alloy Al 2024-T3/Al 7075-T6 structures will improve its stretch formability.

Table 4.3 Formability of FSW Al 2024-T3/Al 7076-T6 structures

Case #	Rot. Vel. RPM	Weld Vel. mm/min.	Ductility Index (% Elong.)	Depth of Plunge at Failure (mm)
Bi-A 1	1300	54.00	6.8	12.09
Bi-A 2	1300	92.10	12.3	16.37
Bi-A 3	1300	146.00	9.9	14.99
Bi-A 4	1300	194.00	7.2	9.14
Bi-A 5	1045	146.00	5.9	11.77
Bi-A 6	1045	92.10	12.5	15.45
Bi-A 7	1045	194.00	7.9	7.62
Bi-A 8	840	117.50	8.9	9.79
Bi-A 9	840	146.00	7.4	9.31

CHAPTER 5: CONCLUSIONS

- Hybrid Manufacturing (HM) technology for net-shape production of monolithic structures for the transportation industry is explored.
- The developed technology combines FSW and stretch forming in order to tailor the properties of the preform to provide a net-shape monolithic structure.
- Obtained results provide an understanding of the effects of the major process parameters in HM for establishing successful monolithic structures that satisfy design requirements and product service conditions.
- In general, high tool rotational velocity combined with slow welding velocity in FSW; enhance stretch formability of the produced monolithic structure.
- The results are organized in process maps that define the process operating conditions that result in reasonable monolithic structure properties.
- Future studies are recommended to investigate the feasibility of the presented HM technology to monolithic structures with more complex geometry using deep drawing processes.

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