GUIDE FOR

THE APPROVAL OF FRICTION STIR WELDING IN ALUMINUM

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Foreword

This Guide provides the guidelines for the approval of friction stir welding procedures, operators and the nondestructive testing requirements for production friction stir welding of aluminum. These guidelines are based on the current knowledge and may be updated as practical experience is gained. The latest knowledge will be considered in approval tests and may require the test program or the range of approval to be adapted accordingly.

This Guide becomes effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of this Guide is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

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SECTION 1 General

1 Scope and Application

This Guide has been developed with the objective of setting out the requirements for the qualification of friction stir welding (FSW) procedures and operators. This Guide also provides guidelines for the production quality control of FSW and the nondestructive testing (NDT) requirements. FSW produces a weld between two abutting workpieces by the frictional heating and plastic material displacement caused by a rotating tool that traverses along the weld joint. This Guide is for the application of FSW for aluminum groove welds. No other joint configuration is considered in this Guide.

Weld procedure and operator qualification requirements apply for FSW of aluminum alloys identified in Ref. 1.

2 References

The following documents form a part of this overall Guide to the extent they are referenced.

Reference Number	*Reference Description*
1	ABS *Rules for Welding and Materials (Part 2)*
2	AWS A3.0 Standard Welding Terms and Definitions
3	ABS *Guide for Nondestructive Inspection of Hull Welds*
4	AWS D1.2/D1.2M Structural Welding Code – Aluminum
5	AWS D17.3/17.3M Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications
6	NASA document PRC-5010C, Process Specification for Pickling, Etching, and Descaling of Metals

3 Definitions

Adjustable Probe (Retractable Pin) Tool – Tool probe length, rotation speed, direction of probe rotation are adjustable.

Advancing Side of Weld – Side of the weld where the direction of tool rotation is the same as the direction of welding.

Direction of Tool Rotation – Rotation as viewed from the spindle that is rotating the tool.

Exit Hole – Hole remaining at the end of a weld after the withdrawal of the tool.

Flash – Material expelled along the weld toe during FSW.

Friction Stir Re-weld – FSW pass upon FSW pass from one side only.

Friction Stir Welding Methods – Methods include, but are not limited to, robotic, single spindle, multiple spindles, adjustable probe (retractable probe) tool, self-reacting (bobbin) tool, and simultaneous two-sided welding.

Heel – Part of the tool shoulder that is at the rear of the tool relative to its forward motion.

Heel Plunge Depth – Distance the heel extends into the workpiece.

Joint Line Remnant – Unmixed and distorted layer of Aluminum Oxide, occurring at the root of the joint faying surfaces, when the joint is welded from one side using anvil backing.

Probe – Part of the welding tool that extends into the workpiece to make the weld.

Retreating Side of Weld – Side of the weld where the direction of tool rotation is opposite to the welding direction.

Self-reacting (Bobbin) Tool – Tool with two shoulders separated by a fixed length probe or an adjustable length probe.

Sweep – Denotes a curve in the horizontal plane.

Tool Offset – The shortest distance from the tool axis to the joint.

Tool Shoulder – Surface of the tool that contacts the workpiece surface during welding.

Tool Rotation Speed – Angular speed of the welding tool in revolutions per minute.

Welding Tool – Rotating component that passes entirely through or partially through the workpiece, and may or may not have a shoulder.

SECTION 2 Weld Procedure Qualification

1 General Considerations

Prior to production welding, the manufacturer or contractor shall develop and qualify FSW procedures. A welding procedure qualification test plate schematic with locations for removal of test specimens is shown in Section 2, Figures 1 and 2. The FSW fabricator shall document the essential elements of Section 2, Table 1 when developing a FSW procedure. Section 2, Table 2 provides the required destructive and nondestructive tests for FSW qualification test assemblies. Each FSW manufacturer or contractor is responsible for the FSW done by their organization and shall conduct the qualification tests required in this Section.

Every weld procedure shall be submitted to and Approved by the ABS Materials Department prior to acceptance. Surveyors shall witness the procedure qualification and test results to their satisfaction.

1.1 Procedure Qualification Limits

The FSW manufacturer or contractor shall adhere to the procedure qualification limits for FSW described in Section 2, Table 1. When welding the procedure qualification test assembly, the welding operator shall be under the full control and supervision of the FSW manufacturer or contractor.

1.2 Test Assembly Size

The procedure qualification test assembly size shall be as shown in Section 2, Figure 1 for square groove welds. The size of the test assembly shall be sufficient to permit removal of the required test specimens from the nominal start, middle, and end of a single weld. The intent of this requirement is to obtain property data at various locations along the weld length to observe any property variations that may exist within a single weld. Friction stir welding of additional test assemblies to furnish test specimens shall not be permitted. Multi-pass FSW will be specially considered.

1.3 Rejection of Test Assembly

If a procedure qualification fails to meet any of the requirements, the test assembly shall be rejected. In such cases, two test assemblies may be welded using the same welding procedure and tested. If the second set of test assemblies fails, that FSW procedure shall be rejected and a new FSW procedure shall be written and tested.

1.4 Transfer of Qualification

Qualification resides with the FSW manufacturer or contractor that performed the qualification testing. A FSW manufacturer or contractor may transfer qualified weld procedures from one FSW machine to another when the FSW machine is of identical model and type. The FSW manufacturer or contractor may use qualified FSW procedures at other facilities which are under the manufacturer or contractor's operational and quality control.

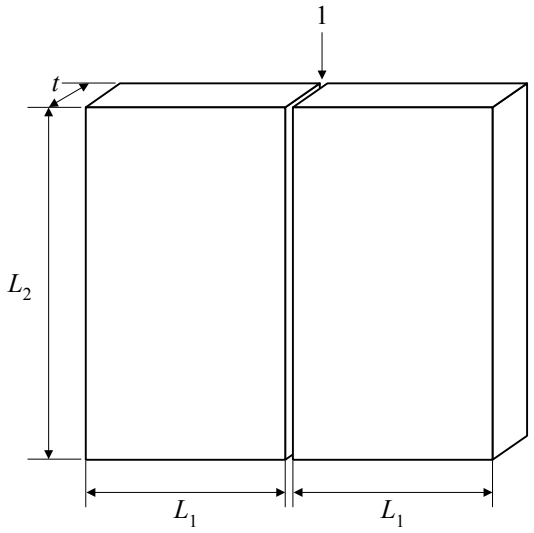
1.5 Transverse Tensile Test Specimens and Transverse Bend Specimens

Transverse tensile test specimens and transverse bend specimens are to be in accordance with Ref. 1. The preparation of macroetch specimens is to be to an appropriate standard to reveal the structure of the weld.

1.6 Fixturing

Special consideration shall be taken for acceptance of procedures where the weld procedure test piece is a different shape or arrangement than the production piece. The fixturing arrangement for production work shall be proven to be equivalent to the procedure qualification fixturing to the satisfaction of the attending Surveyor.

FIGURE 1
Butt Joint Test Assembly



Notes:

1	Joint preparation and fit-up, as specified in WPS
L_1	Minimum 150 mm (6 in.)
L_2	Minimum 500 mm (20 in.)
t	Production material thickness

FIGURE 2
Location of Test Specimens (8)

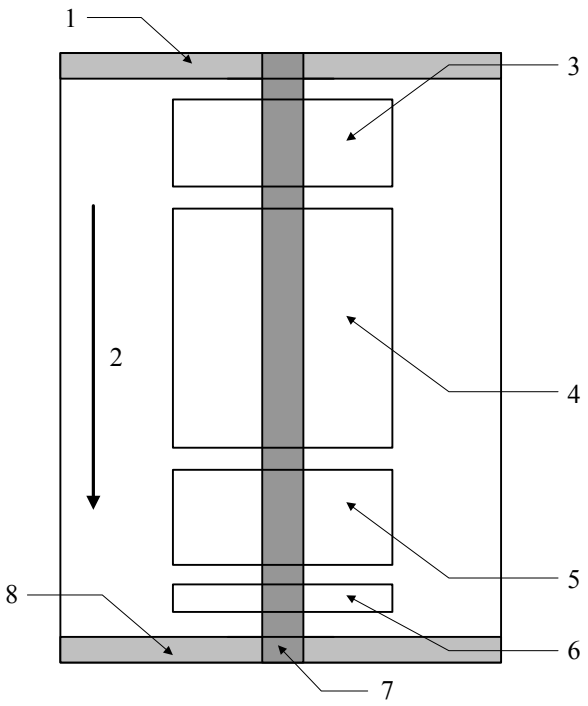


FIGURE 2 (continued)
Location of Test Specimens [8]

Notes:

1 Discard at least 50 mm (2 in.) from each end of the test assembly

2 Direction of welding

3 Start area for:
– 1 tensile test specimen
– root and face bend test specimens [1]
– macroetch specimen

4 Middle area for:
– 1 tensile test specimen
– root and face bend test specimens [1]
– macroetch specimen

5 End area for:
– 1 tensile test specimen
– root and face bend test specimens [1]
– macroetch specimen

6 Not used

7 Weld

8 150 mm (6 in.) minimum between Start area 3 and Middle area 4 and between Middle area 4 and End area 5

Note 1: For welds fabricated from both sides, side bend specimens may be substituted.

2 Qualification of Weld Repair Procedures

Welding repair of friction stir welds by either FSW or arc welding processes requires qualification as indicated in Section 2, Table 1, Essential Elements 26 or 27. The repair procedure shall include the details of repair including the qualified Weld Procedure Specification (WPS). If base material nominal tolerances are outside the qualified thickness range, a change in material thickness ±5% from that qualified does not require requalification so long as all other essential elements remain unchanged and the base material thickness is within the nominal tolerances. The repair WPS procedure qualification test assembly size shall be as shown in Section 2, Figure 1. The size of the test assembly shall be sufficient to permit removal of the required test specimens from the nominal start, middle, and end of the repair weld. The intent of this requirement is to obtain property variability that may exist for the various regions of a single friction stir weld repair. Friction stir welding of additional weld repair test assemblies to furnish test specimens is not permitted.

For a given weld repair method, the entire thickness range may be qualified by testing at the minimum and maximum thickness for a given defect type for each alloy and temper combination identified in Section 2, Table 1.

3 Operator Qualification

The FSW fabricator shall perform the destructive and nondestructive tests for FSW operator qualification test assemblies in accordance with Section 2, Table 3.

The FSW fabricator shall adhere to the performance qualification limits described in Section 2, Table 1.

Section 2, Table 1 indicates the material thickness range over which a weld operator may be qualified using a specific weld procedure.

The operator qualification test assembly size shall be as shown in Section 2, Figure 1. The size of the test assembly shall be sufficient to permit removal of the required test specimens from the nominal start, middle, and end of the repair weld. The intent of this requirement is to obtain property data for various regions along the weld length. Friction stir welding of additional test assemblies to furnish test specimens is not permitted.

4 FSW – Weld Procedure Specification (WPS) and Welder Performance Qualification Record Requirements (WPQR)

The FSW – Weld Procedure Specification (WPS) and Performance Qualification Requirements (WPQR) that are developed in accordance with Subsections 2/1 through 2/3 and Ref. 1 shall be provided to ABS.

TABLE 1
Essential Elements of a Friction Stir Welding Procedure

	Element	*Limits*[1]	*Requires Requalification* [2]	*Notes*
1.	Base material composition or condition	Specific alloy used in qualification test	Change in alloy or temper (to a higher-strength temper within the same alloy group)	
2.	Base material thickness	Specific thickness used in qualification test	Change in material thickness ±5% [3]	
3.	Base material cleaning	Identified method	Change in method from abrasive to chemical or vice-versa	Shall include degreasing and removal of oxides from plate edges within 8 hours of welding
4.	Applicable joint designs – gap and sweep of adjoining members (reference or sketches)	Joint type used in qualification testing sets limits	Change in joint type or variations – allowable range ±1 mm (0.039 in.)	A min/max range may be qualified.
5.	Process	Shall indicate whether fixed-probe or self-reacting/ bobbin or adjustable probe/ retractable pin mode is employed	Change from the qualified mode	
6.	Machine model and type	Specific model, type, and cooling method	Change to a different model type, or cooling method	
7.	Tool holder model and type	Specific model, type, and cooling method	Change to a different model or type	Shall include whether tool holder employs active cooling
8.	Fixturing method [2]	Limits to method applied	Change to method applied	Shall include method of fixturing (e.g., clamping, etc.). Shall include whether fixturing employs active cooling, hydraulic, fixed clamping, adjustable
9.	Travel speed	Specific speed used in qualification test (≤ 5% variation allowed)	An increase or decrease of more than 5%	Speed of tool travel traversing the workpiece
10.	Position	Position used in qualification test	Change in position	
11.	Preheat/Interpass/Post-Weld Heat Treatment (PWHT)	Preheat/interpass/PWHT used in qualification test	Change in preheat/interpass/ PWHT	
12.	Weld type – FSW (variation limited)	Variation tested	Change from or to double-sided or multiple passes	Single-sided, double-sided, number of passes

TABLE 1 (continued)
Essential Elements of a Friction Stir Welding Procedure

	Element	*Limits*[1]	*Requires Requalification* [2]	*Notes*
13.	Welding tool and probe	Specific tool material, design, and mode (i.e., fixed, bobbin, etc.) used in qualification test	Any change to tool and probe type from that used in qualification test	Tool and probe material; tool and probe geometry/design [e.g., shoulder diameter, probe diameter, probe length, probe shape (conical, cylindrical, etc), threads or no threads, number of flats (if applicable) tool ID, probe ID (if two-piece tool) and shoulder design]; fabrication process (i.e., fixed, bobbin, retractable). A tool is a component that is inserted into the tool holder that consists of a larger diameter shoulder and a protruding smaller diameter probe. A tool can be either a monolith or a two-piece component. A probe is a component protruding from the shoulder of the FSW tool below the surface of the parent metal during welding.
14.	Welding tool inspection and cleaning [2]	Method used in qualification test	A change in tool inspection and cleaning method	Indicate the condition of tool and probe prior to weld (i.e., new, used and cleaned, used and not cleaned, indication of wear on tool). Indicate cleaning method.
15.	Process control method [2]	Method used in qualification test	Change, for example, to or from force or position control	Force or Position control
16.	Process loads	Setting used in qualification test (≤ 10% variation allowed)	> 10%	Z-axis (forge) loads at a minimum; recommend monitoring X-axis loads
17.	Tool rotational speed	Setting used in qualification test (≤ 5% variation allowed)	> 5%	During plunge, dwell time at start and end of weld, and during welding. The dwell time at the start of weld is the time interval between the completion of tool plunge and the start of travel. The dwell time at end of weld is the interval of time after travel has stopped but before the rotating tool has begun to withdraw from the weld.
18.	Tool rotational direction	For "featured" tools designed for specific rotational direction, qualification is limited to direction used in qualification testing. For featureless tool, one direction qualifies the other.	Change to or from clockwise or counterclockwise if "direction-specific" tool design used (e.g., threaded tool designed to rotate in a specific direction)	Clockwise (CW) or counterclockwise (CCW)

TABLE 1 (continued)
Essential Elements of a Friction Stir Welding Procedure

	Element [2]	*Limits* [1]	*Requires Requalification*	*Notes*
19.	Lateral tool offset and direction	Tool offset and direction used in weld procedure specification	Change from tool offset plus or minus tolerance specified in weld procedure qualification or change in rotational direction of a tool with lateral offset.	Distance from the tool centerline axis to one side of the joint centerline. Tool is either offset towards the advancing side or retreating side of the weld
20.	Tool tilt angle	Pitch angle(s) used in qualification test	Change in pitch angle outside range used in qualification test.	Angle of tool (vertical axis) with respect to workpiece surface
21.	Side tilt angle	Side tilt angle(s) used in qualification test	Change in side tilt angle outside range used in qualification test.	Angle by which the tool is inclined away from the vertical, in a direction transverse to the welding direction.
22.	Post weld surface dressing	Not permitted prior to NDT and mechanical testing		
23.	Tack welding	Tacks shall be welded by a qualified welder using an approved WPS. Tacks shall be no more than 5% of weld length.	Tacks > 5% of weld length	Method, length, and frequency along length of joint line
24.	Exit hole repair or removal method [2]	Any demonstrated exit hole repair or removal procedure (can be qualified separately from FSW procedure)	Change in exit hole repair procedure. Not required if exit hole is removed.	Method used to eliminate the exit hole
25.	Restart procedure [2]	Limited to procedure qualified, if any	Change from the qualified procedure	Shall describe procedures for restart weld in case of machine malfunction or tool breakage. Procedure shall include tool removal method, termination area cleaning and preparation method, restart location relative to weld termination point.
26.	Friction Stir Weld Over a Friction Stir Weld (i.e., Friction Stir Re-weld) [2]	Any FSW over an existing FSW shall require a separate FSW procedure specifically approved by ABS Materials prior to implementation	Any change in the setup of a friction stir re-weld over an existing friction stir weld shall require a new qualification.	
27.	Fusion Weld Repair of a Friction Stir Weld [2]	Base metal used in qualification shall be friction stir welded using the same number of passes as the friction stir weld to be repaired.		
28.	Shielding Gas (special applications)	Composition, flow rate, addition or deletion, etc.	Change requires requalification	

Notes:

1 Any change in an essential element requires requalification if it is outside the allowable limits above.

2 Facility shall provide descriptive narrative related to application and limits of this essential element. For narrative related to Element 26 or Element 27, the precise nature of the repair and why it is needed shall be specified. The qualified repair procedure shall only be used to repair the specific defect(s) indicated in the narrative.

3 In production, if base material nominal tolerances are outside the qualified thickness range, a change in material thickness ±5% from that qualified does not require requalification so long as all other essential elements remain unchanged and the base material thickness is within the nominal tolerances.

TABLE 2
Weld Procedure Qualification Test Requirements (1, 2, 3, 8)

Test Methods	*Testing Requirements*	*Comments*
Transverse Tensile (5)	3 specimens	Specimens taken from nominal start, middle, and end of weld.
Transverse Guided Bend (4, 5)	3 face bends and 3 root bends	1 face bend specimen and 1 root bend specimen taken from each area – nominal start, middle, and end of weld. For thickness > 19 mm (3/4 in.) 3 side bends may be substituted for the 3 face bends. The 3 root bends are still required.
Macroetch (5)	3 specimens	Specimens taken from nominal start, middle, and end of weld.
Visual (5, 6)	100% required prior to other NDT	
Ultrasonic (6)	100% required	
Radiographic Inspection (6)	100% required	
Etched Dye Penetrant (7)	100% required	Unless qualified for an unetched specimen

Notes:

1 Testing specimens and results to be to the requirements of Ref. 1.

2 Repair of qualification test assemblies is not permitted.

3 Retests of qualification test assemblies are not permitted.

4 For welds fabricated from both sides, a total of six side bends shall be used in lieu of three face and three root bends.

5 Visual inspection shall be performed prior to any destructive testing.

6 NDT procedures and requirements are provided in Ref. 3 ABS *Guide for Nondestructive Inspection of Hull Welds*. Acceptance criteria shall be to Class A. Additional NDT requirements are in Subsection 3/6.

7 For procedure qualification in accordance with Ref. 1, photographs of chemical polish (etch) specimens shall be provided to ABS Materials for review and approval prior to beginning production. Ref. 6, NASA document PRC-5010C, Process Specification for Pickling, Etching, and Descaling of Metals, may be consulted for guidelines on etchant selection.

8 A welding procedure qualification test plate schematic with locations for removal of test specimens is shown in Section 2, Figure 2.

9 The tensile strength of each specimen, when it breaks in the weld, is not to be less than the minimum specified tensile strength of the base metal. When broken in the base metal and the weld shows no signs of failure, is not to be less than 95% of the minimum specified tensile strength of the base material.

10 Guided bend tests after bending shall not show any cracking or other open defect exceeding 3.2 mm (1/8 in.).

11 NDE acceptance criteria shall be in accordance with the requirements of Class A welds as contained in ABS Guide for Nondestructive Inspection of Hull Welds.

TABLE 3
Operator Qualification Test Requirements (2, 3, 6, 8)

Test Methods	*Testing Requirements*	*Comments*
Transverse Tensile (1)	3 specimens	Specimens taken from nominal start, middle, and end of weld.
Transverse Guided Bend (1, 3, 4)	3 face bends and 3 root bends	Specimens taken from nominal start, middle, and end of weld. F For thickness > 19 mm ($^3/_4$ in.) 3 side bends may be substituted for the 3 face bends. The 3 root bends are still required.
Macroetch (1, 4)	3 specimens	Specimens taken from nominal start, middle, and end of weld.
Visual (5)	100% required prior to other NDT	
Ultrasonic (5)	100% required	
Radiographic Inspection (5)	100% required	
Etched and Unetched Dye Penetrant (7)	100% required	Unless qualified for an unetched specimen.

Notes:

1 Testing specimens and results to be to the requirements of Ref. 1.

2 Qualifying an operator for friction stir welding with one 5000 series base material of NAVSEA Tech Pub 248 qualifies that operator to weld all 5000 series base materials $^2/_3T$ to $4T$ of the original test within the requirements of this Guide. Similarly, qualifying an operator to friction stir weld one 6000 series aluminum alloy qualifies that operator to weld all 6000 series aluminum alloys $^2/_3T$ to $4T$ of the original test within the requirements of this Guide. For other materials, approval of ABS NED Materials or Houston Materials is specifically required.

3 Repair of qualification test assemblies is not permitted.

4 For welds fabricated from both sides, a total of six side bends shall be used in lieu of three face and three root bends.

5 NDT procedures and related requirements shall conform to Ref. 3 ABS *Guide for Nondestructive Inspection of Hull Welds* and Ref. 1. Additional NDT requirements are in Subsection 3/6.

6 Operators qualifying for friction stir re-weld of an existing friction stir weld shall be qualified to a specific procedure according to this document.

7 Ref. 6 NASA document PRC-5010C, Process Specification for Pickling, Etching, and Descaling of Metals, may be consulted for guidelines on etchant selection.

8 A welding procedure qualification test plate schematic with locations for removal of test specimens is shown in Section 2, Figure 2.

9 The tensile strength of each specimen, when it breaks in the weld, is not to be less than the minimum specified tensile strength of the base metal. When broken in the base metal and the weld shows no signs of failure, is not to be less than 95% of the minimum specified tensile strength of the base material.

10 Guided bend tests after bending shall not show any cracking or other open defect exceeding 1.6 mm ($^1/_{16}$ in.).

11 NDE acceptance criteria shall be in accordance with the requirements of Class A welds as contained in ABS Guide for Nondestructive Inspection of Hull Welds.

SECTION 3 FSW Production Quality Control and NDT Requirements

1 Records

FSW fabricator records are required for each friction stir weld. The records are intended to provide documentation that each FSW meets all the requirements of this Guide. These records shall document that all required inspections were performed and include inspection results. The records are to be kept in accordance with the Rule requirements.

2 Inspection Before Production FSW

2.1 Verification Before Welding

Before welding, the FSW Fabricator shall verify the following:

i) The essential elements of the production job are consistent with the approved qualification as required by Section 2, Tables 1 and 2.

ii) The operator has a valid qualification/certification for the intended job in accordance with Section 2, Table 3.

2.2 Joint Setup Variability

A joint setup with sweep (horizontal) or joint misalignment (vertical) no greater than ±1 mm (0.039 in.) is required. For sweep or joint misalignment greater than ±1 mm (0.039 in.), a separate procedure is required which is specific to the maximum sweep and misalignment expected in production and is keyed to the maximum weld length, the location of the sweep or misalignment within the weld length, and where the tool is set up initially. Sweep and alignment limits shall be verified at the weld start, stop, and midpoint over the weld line. Sweep and misalignment shall be measured and recorded prior to production welding as to joint setup, and verified after welding to confirm shifting of the joint did not occur during welding. If the FSW has qualified procedures which include automated seam tracking or joint position and alignment, monitoring the above may be eliminated with the agreement of the attending Surveyor.

3 Inspection During Production FSW

Continuous in-process monitoring of all friction stir welds shall be carried out. At suitable intervals process records should be checked to verify that all essential elements as specified are in compliance with the approved procedures. Corrective action shall be taken upon detection of discrepancies. The inspection discrepancies and any corrective actions shall be documented to the satisfaction of the attending Surveyor.

Surveyor shall attend initial fabrication stages sufficiently to verify that fixtures used for restraining the work are capable of maintaining the joint within the parameters of the weld procedure. Initial panels shall have additional NDE as requested by the Surveyor to verify the quality of the work.

4 Inspection After Production FSW – Visual Inspection (VT)

100% visual inspection shall be performed on all completed welds in accordance with Ref. 3. Completed friction stir welds shall meet the following requirements.

4.1 Exit Hole Uniformity

The exit hole is to be examined. A deformed circle of material remains around the probe. Where the exit hole uniformity is noted to be less than 75 percent complete, ultrasonic inspection shall be performed in accordance with Ref. 1 or ~~4~~ 3 for an additional 10 percent of weld length identified in Subsection 3/3, or 10% minimum. The additional 10% ultrasonic inspection shall be randomly selected, and inspection shall be performed in accordance with the ultrasonic inspection requirements as set forth in Subsection 3/6.

4.2 Herring Bone or Chevron Marking

A herring bone structure or chevron marking are acceptable attributes that may be present at the weld root in a production friction stir weld. These imperfections shall be noted. Removal is recommended prior to bend testing of the root.

4.3 Flash

Prior to removal of flash, regions within friction stir welds containing excessive flash shall be marked on the plate, and these areas shall be inspected for dimensional conformance as required in 3/4.4. Additional inspection by dye penetrant and ultrasonic inspection as called out in 3/5.1 and 3/5.2 is to be to the satisfaction of the Surveyor.

4.4 Dimensional Requirements

Dimensional requirements of the weld and adjacent base material shall be checked to verify that the thickness of the weld and its adjacent base metal are to the satisfaction of the Surveyor.

4.4.1 Thickness Variations (Lack of Fill/Concavity of Weld Joint)

Weld concavity depth (face or root) is not to exceed 0.8 mm ($^1/_{32}$ in.) or 10 percent of the adjacent base metal thickness, whichever is less. For base metal thickness equal to or greater than 12.7 mm ($^1/_2$ in.), weld concavity up to 1.6 mm ($^1/_{16}$ in.) is allowed if the accumulated length of weld concavity exceeding 0.8 mm ($^1/_{32}$ in.) does not exceed 15 percent of the joint length or 304.8 mm (12 in.) in any 914.4 mm (36 in.) length of weld, whichever is less.

4.5 Butt Joint Alignment

Height offset misalignment, extrusion to extrusion, is to be less than or equal to 0.2 times the base material thickness or 2 mm (0.078 in.), whichever is less, unless specifically qualified.

4.6 Irregular Width

Width variation of the welded assembly is to be within the limits of the design specification.

4.7 Root Reinforcement

Root reinforcement is to be less than or equal to 10% of the base material thickness.

4.8 Cracks, Porosity, Lack of Penetration

No cracks, porosity, or lack of penetration are allowed.

4.9 Visual Examination Records

Visual examination shall be recorded for each weld on a panel. The visual exam shall include the areas in the start and stop sections that may be trimmed off by the fabricator or the purchaser. These areas may be so noted if trimmed by the fabricator.

5 Other Inspection After FSW

5.1 Macroetch

One macroetch test is required, preferably, from a prolongation piece (run-off tab) at the beginning and end of each shift or where an essential element or process is changed. The preparation of macroetch specimens is to be to an appropriate standard to reveal the structure of the weld. The macroetch specimens are to be examined by eye or low-powered (5X) lens for any imperfections, including porosity, lack of bonding, joint line remnant, inadequate penetration greater than 0.8 mm ($^1/_{32}$ in.) or 10% of the thickness of the weld, whichever is less, or lack of one central nugget. If a macroetch test fails, the FSW fabricator shall investigate production welds back to the previously-accepted macroetch test. Acceptance of the investigation is to be to the satisfaction of the Surveyor.

5.2 Penetrant Testing (PT)

Penetrant testing is to be performed at two random inspection sites 457.2 mm (18 in.) in length on each fabricated panel, in accordance with 3/6.2.

5.3 Ultrasonic Testing (UT)

Ultrasonic testing is to be performed at two random inspection sites 457.2 mm (18 in.) in length on each fabricated panel, in accordance with 3/6.3. UT sites are to be different from the sites used for PT.

5.4 Radiographic Testing (RT)

Radiographic testing may be performed in lieu of UT for weld thickness less than or equal to 6.35 mm ($^1/_4$ in.), in accordance with 3/6.4.

5.5 Batch Testing Alternative

For production of FSW panels performed in batches, an alternative inspection plan may be proposed and accepted by the Surveyor. The inspection plan shall be effective at locating all common FSW defects, including internal voids and off seam conditions in the middle of the welds and at the ends. A batch is defined as a sequential production run of panels with multiple friction stir welds with one FSW procedure, and can be of any number 1, 5, 10, or other

6 FSW NDT Acceptance Requirements

NDT procedures and personnel are to meet the requirements of Ref. 3 and as detailed in the notes to Section 2, Tables 2 and 3. Inspection records are to be in accordance with Rule requirements.

6.1 Visual Inspection (VT)

Visual inspection shall be performed to evaluate physical attributes of the friction stir weld that help provide confirmation that proper operating conditions were maintained during fabrication. These attributes include:

i) Exit hole uniformity

ii) Flash

iii) Chevron markings

iv) Dimensional variations in thickness (lack of fill)

v) Misalignment

vi) Cracks, porosity, lack of penetration

Where VT is required, both top and bottom of each FSW shall be inspected to the maximum extent possible.

6.2 Penetrant Testing

Where required, PT shall be performed in accordance with Ref. 3. The acceptance criteria shall be in accordance with Ref. 3.

6.2.1 Surface Preparation for Penetrant Testing

Following visual inspection and documentation of surface anomalies noted during inspection, flash, overlapping material, and other weld surface irregularities which may interfere with the interpretation of the dye penetrant test results shall be removed by a method that does not degrade parent metal properties or interfere with the inspection. In addition, prior to liquid penetrant inspection, the surfaces to be inspected shall be sanded or etched to remove a minimum of material, but at least 0.025 mm (0.001 in.) using a sanding or etching process. The requirement for the use of sanding or etching prior to PT inspection shall be determined and qualified as follows:

Following visual inspection and documentation of surface anomalies noted during inspection, flash, overlapping material, and other weld surface irregularities which may interfere with the interpretation of the dye penetrant test results shall be removed by a method that has been proven not to degrade parent metal properties or interfere with the inspection. In addition, prior to liquid penetrant inspection, the surfaces to be inspected shall be sanded or etched to remove a minimum of material, but at least 0.025 mm (0.001 in.), using a sanding or etching process. The requirement for the use of sanding or etching prior to PT inspection shall be determined and qualified as follows:

i) The effect of the sanding or etching process on smearing inspection surface shall be evaluated using the recommended practice of AMS 2644 Type 2 penetrant sensitivity test panels (aluminum quench crack panels).

ii) The acceptability of the proposed sanding or etching process shall be based on the PT results obtained with the candidate sanding or etching process applied to half of the quench crack panel, as compared to the results obtained with no sanding or etching on the other half of the panel. All of the other PT procedure parameters shall be the same for both sides of the panel. The minimum penetrant dwell time and the minimum development time allowed by the PT procedure shall be used. The Level III PT examiner shall determine if the proposed sanding or etching process is warranted for use when the indications obtained with the proposed sanding or etching process are compared to (or there is a minimum effect as a result of the sanding or etching) those obtained with the unsanded side of the panel.

iii) Documentation of the qualification of the PT procedure shall include photos of both sides of the processed panel and shall be provided to ABS Materials.

NASA document PRC-5010C, Process Specification for Pickling, Etching, and Descaling of Metals, may be consulted for guidelines on etchant selection.

6.3 Ultrasonic Testing (UT)

Ultrasonic inspection shall be in accordance with Ref. 3.

6.3.1 Thin Materials

For materials less than 6.35 mm ($^1/_4$ in.) thick, radiographic (x-ray) testing utilizing Class 1 film and aluminum IQIs may be substituted for UT at the discretion of the Level III.

6.3.2 Attenuation Check

The ultrasonic inspection procedure shall include an attenuation check between the friction stir weld and the base metal using a two transducer shear wave pitch-catch arrangement. Any measured increase in attenuation noted in the friction stir weld material shall be compensated for by adding the appropriate number of dB to the instrument after calibration on the weld calibration block.

6.4 Radiographic Testing (RT)

Radiographic Testing shall be in accordance with Ref. 3.