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GUIDELINES FOR FRICTION STIR WELDING

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The Contractor shall review Drawing 19207-12472301 Rev. A, 19207-12479550 Rev. A, and AWS welding specifications provided by the COR 30 DAC for steel and aluminum and prepare draft guidelines, to be submitted IAW A005, for FSW to be incorporated into a future Department of Defense welding standard.

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TASK OBJECTIVE

The Contractor shall review Drawing 19207-12472301 Rev. A, 19207-12479550 Rev. A, and AWS welding specifications provided by the COR 30 DAC for steel and aluminum and prepare draft guidelines, to be submitted IAW A005, for FSW to be incorporated into a future Department of Defense welding standard.

TECHNICAL PROBLEMS

Not applicable

GENERAL METHODOLOGY

A) Review current and inactive Department of Defense fusion welding codes and standards to become familiar, from a standards and specification perspective, with welding requirements and typical content.

B) Review existing industry standards for the friction stir welding process.

C) Review industry and academia literature for FSW applied to ballistic structures.

D) Identify the specific current ballistic fusion welding requirements that require revision, or are inapplicable, when applied to FSW.

E) Identify specific FSW requirements that require revision, or are inapplicable, when applied to ballistic structures.

F) Prepare a preliminary manufacturing process standard for friction stir welding ballistic armor.

TECHNICAL RESULTS

The following is a summary of the unique characteristics and requirements for the design and manufacture of friction stir welded ballistic structures. See Appendix A for definitions of FSW terminology.

A) Design Considerations

1) Location of exit hole - Because the FSW process results in a large void at the termination point of the weld, the effects the exit hole will have on structural integrity must be considered. The engineering drawing should specify whether the weld exit hole should be removed or, if not, the hole's location. Techniques to eliminate an exit hole include; use of an exit block, a sacrificial extension of the part, or filling by a secondary welding method. If engineering analysis indicates

that the presence of an exit hole does not affect structural integrity, the hole may be left in a “no-fill” condition. However, appropriate non-destructive testing should be used to confirm the absence of flaws in this area

2) Workpiece and base material thickness - The maximum thickness capability of FSW is currently limited to two inches. However thicker base materials may be acceptable with further research and development.

3) Joint design – Current military standards specify eight joint types approved for fusion welding of ballistic structures. FSW has equivalent or similar joint designs (see Appendix B) however dimensional limitations and relationships are lacking, except for one characteristic of an FSW lap joint. See Figure 1.

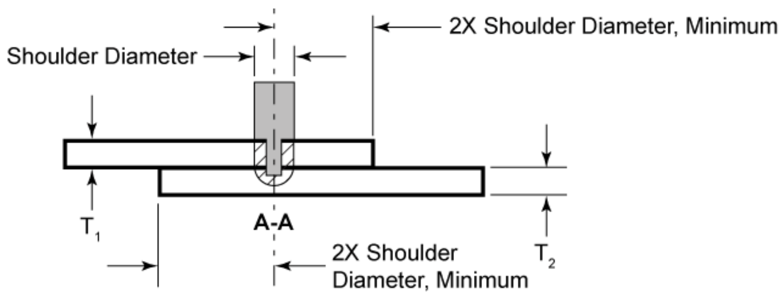
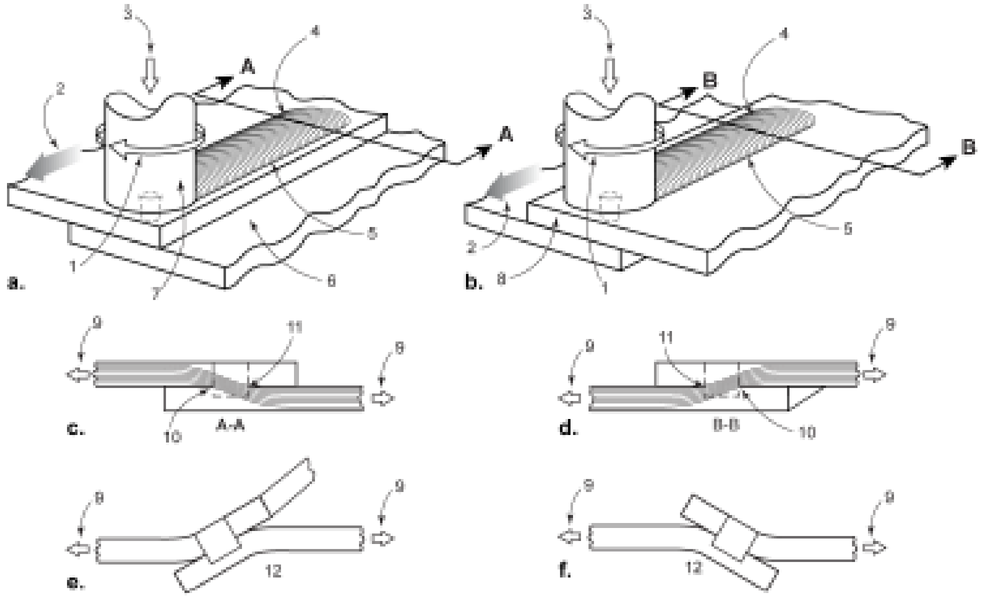


Figure 1 – Lap Weld

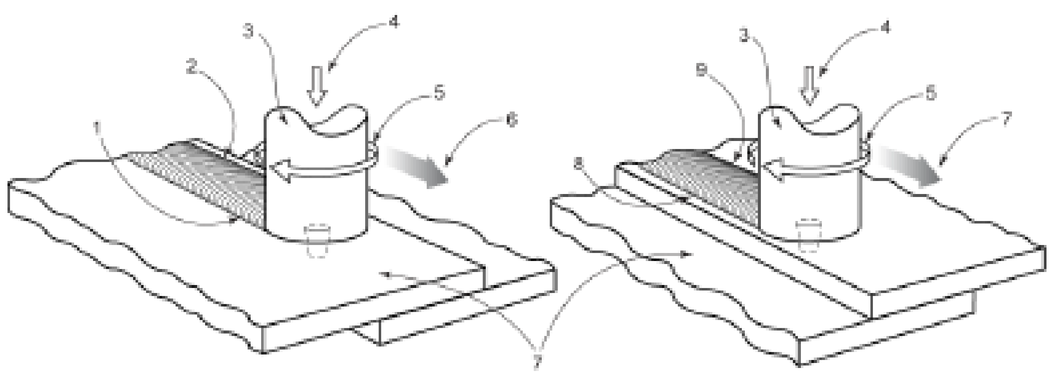
4) FSW lap weld - A friction stir lap weld needs to be differentiated from all other lap welds to avoid any misunderstanding of its uniqueness. Conventional FSW is an asymmetric process. For example, one side of the weld is heated more than the other side. Another example of its asymmetry is the difference in strength between the advancing side and retreating side of the weld. Depending on whether the advancing side or the retreating side of the weld is near the edge of the sheet, then the stronger or weaker side of the joint can be placed on the stressed side of the weld, as shown in Figure 2. This is critically important and depends on the advancing near edge or retreating near edge configuration, as shown in Figure 3. *(From ISO/DIS 25239-2)*



Key

1 direction of tool rotation
2 welding direction
3 axial force
4 retreating side
5 advancing side
6 lower workpiece
7 FSW tool
8 upper workpiece
9 tensile force
10 tensile stressed side of upper workpiece
11 tensile stressed side of lower workpiece
12 joint rotation

<u>FIGURE 2 – Lap Weld Strength *(from ISO 25239)*</u>



Key

1 retreating side
2 advancing side is near the weld face sheet edge (ANE)
3 FSW tool
4 axial force
5 direction of tool rotation
6 welding direction
7 workpiece
8 retreating side is near the weld face sheet edge (RNE)
9 advancing side

<u>FIGURE 3 – Advance vs. Retreating Side *(from ISO 25239)*</u>

5) Materials – Two of the three existing industrial standards (AWS and NASA) for FSW are specifically for aluminum alloys applied to aerospace applications. The third (ISO) does not specify material restrictions but is very similar to the AWS standard. Aluminum, steel, titanium and magnesium alloys have all been used in similar and dissimilar metal FSW joints.

B) Process and Fabrication Considerations

1) Shielding gas – As it is for typical fusion welding methods, a shielding gas is not required for FSW except when titanium is used as a base material. To avoid oxide contamination when welding titanium, the space immediately surrounding the active welding tool must be free of oxygen. Any typical welding-grade gas is appropriate.

2) Process temperature – The maximum temperature attained in the Heat Affected Zone (HAZ) of the weld during the FSW process is typically 70-80% of the solidus point temperature of the base material.

3) FSW tool design –

a) The material selected for an FSW tool must be sufficiently harder than the intended base material so that the expected erosion of the tool will be negligible and not affect the metallurgy of the weld zone.

b) The material selected for an FSW tool must have a melting point higher than that of the intended base material.

c) The diameter of the tool shoulder is typically 2-3 times that of the intended base material thickness.

d) The tool pin length is typically 0.020 inches shorter than the thickness of the intended base material.

e) The geometries used for tool pin design vary according to the base material and include; solid profiles, cylindrical and conical shapes, threaded, scrolled, and fluted.

f) The engineering drawing for an FSW tool should specify the location for tool identification markings.

g) Figure 3 and Table 1 indicate the tool design variables.

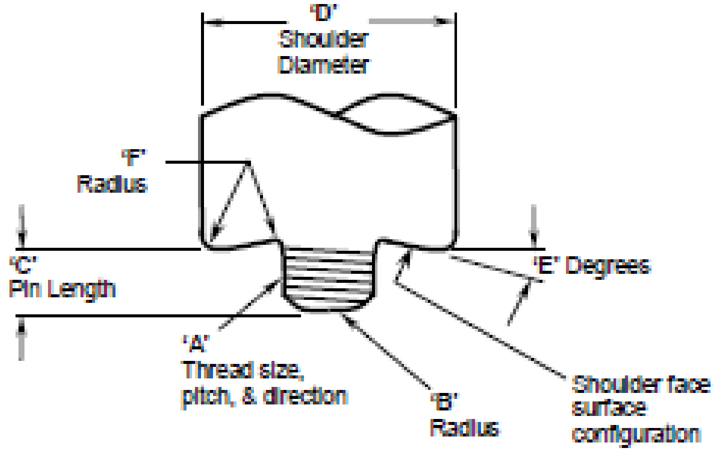


FIGURE 3 *(from NASA PRC-014)*

TABLE 1 - FSW Tool Design Parameters

Variable (Figure 3)	Permitted Process Range[1]
A - thread size, pitch, direction	None
B - end radius	± 0.03"
C - pin length	± 0.002"
D - shoulder diameter	± 0.06"
E - shoulder draft angle	± ½ °
F - shoulder radii	± 0.03"
Pin diameter or conical pitch	± 0.002"
Shoulder feature (flat, scrolled, etc)	None
Pin thread/tool rotation direction	None
Pin thread type	None
Tool material	n/a
Tool material temper	n/a
Tool coating	n/a

1 *From NASA PRC-014 Process Specification for FSW*

4) FSW tool use –

a) Prior to production welding, newly fabricated pin tools should be tested by a trial weld using the same base material alloy, temper, and thickness and production-representative conditions (speeds and loads). The tool should be inspected for signs of wear or damage.

b) Tools should be permanently identified for process quality tracking.

c) Spindle rotation direction should be specified for the specific pin tool thread direction (RH or LH). Spindle rotation should be CW for LH pin threads and CCW for RH pin threads. For non-threaded pins, spindle rotation may be either direction but should be specified for the specific FRW process and joint.

5) Pre-weld joint preparation and fit-up -

a) Due to the solid-state nature of FSW, any weld position is allowed provided the tool and spindle have adequate operating space.

b) For some base material propertied, pre-heating the joint may improve or assist the FSW process. When employed, the heat source is mounted to the spindle axis and travels ahead of the tool spindle.

c) A pre-weld gap between faying surfaces may introduce cavities into the joint and should be avoided.

d) If required for proper fit-up, tack (or temporary) welding of workpieces by FSW or fusion welding is acceptable. If a tack weld lies along the weld path, it shall be entirely consumed by the final FSW process. To avoid introducing impurities into the FSW, the tack weld surface should be thoroughly cleaned before final welding.

6) Post-weld surface - A common post-weld feature of FSW is the toe flash that appears at the outer edge of the weld path. Minor flash is acceptable, yet it should be removed by sanding, grinding, or machining. However excessive flash may be an indication of improper welding parameters.

7) Tool position for dissimilar materials – When joining dissimilar materials, the tool pin should be offset from the joint centerline in the direction of the softer material so that the outer surface of the pin is aligned with the edge of the harder material.

8) FSW process parameters – Table 2 lists the possible variable parameters of the FSW process. Variations of any of these parameters may affect the weld quality and therefore a weld joint should be thoroughly inspected after one or more of these parameters are modified.

9) In-process monitoring – The following FSW parameters should be monitored during the welding process:

a) Amount of flash

b) Spindle/tool forces

c) Travel and tool rotation speeds

d) Weld width (varying width is indicative if fluctuating axial force)

10) Repairs - FSW may be used to repair or rework a weld joint or material flaw.

C) <u>Weld Operator Considerations</u>

1) Qualification – An FSW welding operator should be required to pass a weld qualification test, similar to the qualifications of fusion welding. A qualification test made with any type of FSW method qualifies only that welding method. This applies to FSW methods that include, but are not limited to, robotic, single spindle, multiple spindles, bobbin tool, retractable probe, or other FSW methods.

2) Knowledge – An FSW welding operator should also be required to demonstrate his/her knowledge of the FSW machine and welding terminology. ISO 25239 *Friction Stir Welding – Aluminum* requires that an operator be tested on their functional knowledge of the FSW welding machine and recommends testing for general welding knowledge.

3) Test welds - FSW weldments for weld tests and test sample locations are shown in Appendix C.

D) <u>Welding Procedure Qualification</u>

Other than the parameters that are specific to the FSW process (See Table 2) and the test weldments (Appendix C), an FSW procedure should adhere to the same qualification procedures as other welding methods.

TABLE 2 - FSW Process Parameters

Variable	Permitted Process Range[1]
Spindle axial force	± 10%
Travel speed	± 10%
Travel spindle rotation speed	± 10%
Machine tool model #	None
Machine tool head model #	None
Pin tool configuration	See Table VI
Pin tool model #	n/a
Joint configuration (lap, butt, etc.)	None
Exit hole location	None
Exit hole filler material	None
Exit hole welding procedures	None
Nominal base material thickness	Dwg. tolerances
Base material alloy type(s)	None
Base material alloy temper(s)	None
Preweld cleaning procedures	None
Allowable joint gap	≤0.015"
Tool or shop aid identification	None
Tack welding filler metal	None
Heat assistance source	None
Heat input from heat source	± 10%
Pin tool travel angle	± ½ °
Pin tool heel plunge depth	± 0.010"
Travel direction	None
Ramp-up/ramp-down speeds	± 10%
Travel start/end dwell times	± 10%
Dwell spindle rotation speeds	± 10%
Spindle rotation direction	None
Heat treat procedures	None

[1] *From NASA PRC-014 Process Specification for FSW*

E) <u>Quality, Inspection, and Testing Considerations</u>

1) Weld samples - FSW weldments for weld tests and test sample locations are shown in Appendix C.

2) Test sample preparation – Because of the inherent differences of metallurgical and strength characteristics between the advancing and retreating sides of the weld, test specimens shall be marked with an advancing/retreating designation prior to testing

3) Inspection methods – The visual, non-destructive, and macroscopic inspection methods that are used for FSW are no different than those for fusion welding. However FSW acceptance criteria are unique (See Table 3).

4) Acceptance criteria – FSW flaws and discontinuities should adhere to those indicated in Table 3.

5) Visual inspection requirements - In addition to the requirements of Table 3, FSW welds should also meet the following visual criteria:

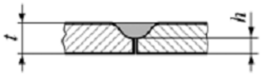
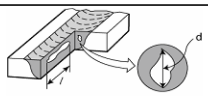
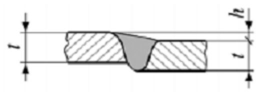
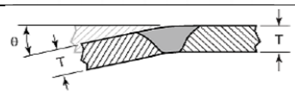
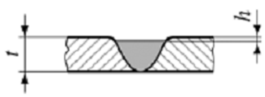
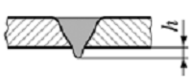
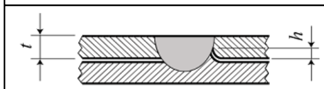
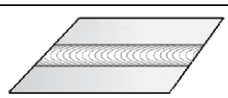
a. Exit hole presence/location should be as specified in the engineering print.
b. The weld width should not show any variations.

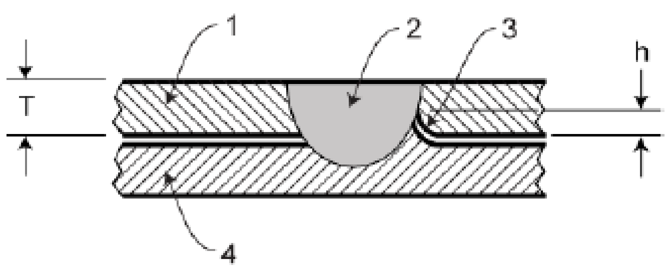
6) Hook - The acceptability of a hook (see Figure 4) within an FSW lap weld is dependent on the fatigue and static load requirements for the weld. The hook size criteria should be defined in the engineering drawing or Weld Process Specification (WPS). The ISO and AWS standards include hook descriptions however they do not specify a specific maximum limit. The NASA standard includes no reference to hooks.

7) Destruction testing – The destructive test methods (bend, tensile, shear) and acceptance criteria that are used for FSW are no different than those for fusion welding.

TABLE 3

Friction Stir Weld Acceptance Criteria

FSW Discontinuity		Acceptance Criteria
	1. Cracks	None allowed
	2. Incomplete joint penetration	None allowed
	3. Inclusions a. Individual size - maximum b. Spacing - minimum c. Accumulated length within any 3-in. of weld	0.33 x T or 0.06-in. whichever is less 4 x the size of the larger adjacent discontinutity 1.33 x T or 0.24-in.
	4. Cavities - internal or open to surface	None
	5. Linear mismatch - maximum	1.05 x base metal thickness tolerance
	6. Angular distortion - maximum	3°
	7. Underfill - maximum a. Full length of weld b. Local defect c. Accumulated length within any 3-in. of weld (only if the weld will not be machined after welding)	0.05 x T 0.07 x T or 0.03 in. whichever is less 0.20 in.
	8 . Weld flash	As specified in WPS
	9. Excess penetration	h<0.12 in.
	10. Hook	AWS and ISO - TBD
	11. Weld surface finish	As specified in WPS



Key
1 Upper workpiece
2. Weld
3. Hook
4. Lower workpiece
h Height of hook
T Thickness of upper workpiece

FIGURE 4 - Hook

8) Weld classifications – None of the existing FSW process standards address ballistic welding. However the three existing FSW process standards each designate separate weld quality criteria for several levels of classification dependent on the end use of the weldment. See Table 4.

TABLE 4 - WELD CLASSIFICATIONS

	Ballistic	Critical	Semi-critical	Non-critical
		Class A	Class B	Class C
		Critical not fail-safe	Load bearing fail-safe	Minor load bearing
U.S. Army Codes	X	X	none	X
AWS D17.3	none	X	X	X
ISO 25239	none	none	none	none
NASA PRC-0014	none	X	X	X

IMPORTANT FINDINGS AND CONCLUSIONS

A) Specific FSW welding joint design characteristics for ballistic structures, which would be similar to those shown in MIL-HDBK-21, have not been developed.

B) FSW has not been evaluated on most of the approved ballistic armor materials and relevant thickness ranges. See Appendix D.

IMPLICATIONS FOR FURTHER RESEARCH

A) An equivalent FSW joint for each of the approved fusion weld ballistic joints should be defined. See Appendix B.

B) For each ballistic FSW weld joint, the relationships of each joint’s dimensional parameters and their effect on weld strength should be studied and optimized.

C) The developed FSW weld joints should be qualified for ballistic application by undergoing ballistic shock testing.

D) For each of the approved ballistic armor materials, the strength and metallurgy of FSW joints should be studied to confirm the applicable of FSW to the respective materials. Because of its solid-state nature, the FSW process may be feasible for joining materials that are known to be difficult or impossible to weld by fusion methods.

SIGNIFICANT HARDWARE DEVELOPMENT

Not applicable

SPECIAL COMMENTS

None

FSW Definitions

(The contents of this appendix are taken from Section 3 of the preliminary FSW standard that has been prepared by Focus: HOPE Center for Advanced Technology.)

3.1 Advancing side of weld. The side of the weld where the direction of tool rotation is the same as the direction of welding. See Figure 3.1.

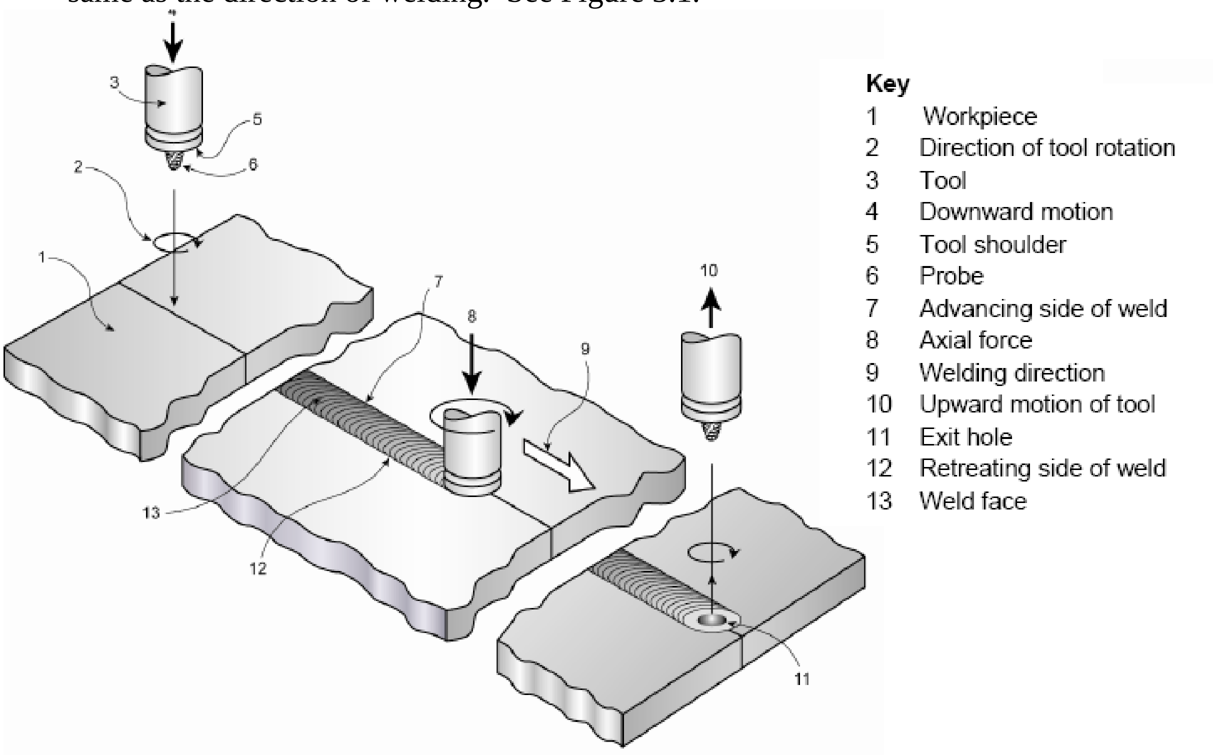


Figure 3.1 —Friction Stir Welding Nomenclature

3.2 Angular distortion of the joint. A distortion between two welded pieces such that their surface planes are not parallel or at the intended angle. See Figure 3.2.

Key

T Thickness of base metal

Θ Angle between original surface and postweld surface

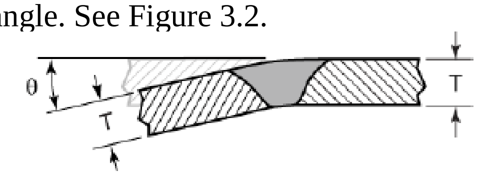


FIGURE 3.2 - Angular Distortion of the Joint

3.3 Anvil. The structure supporting the root side of the joint.

3.4 Axial force. Force applied to the work piece along the axis of tool rotation. See Figure 3.1

3.5 Bobbin tool. A FSW tool with two shoulders separated by a fixed length or an adjustable length pin. See Figure 3.3. *Note - The self-reacting bobbin tool allows the shoulders to automatically maintain contact with the workpiece.*

Key

1 Workpiece
2 Direction of tool rotation
3 Upper tool body
4 Welding direction
5 Upper tool shoulder
6 Probe
7 Lower tool body
8 Lower tool shoulder
9 Reactive forces

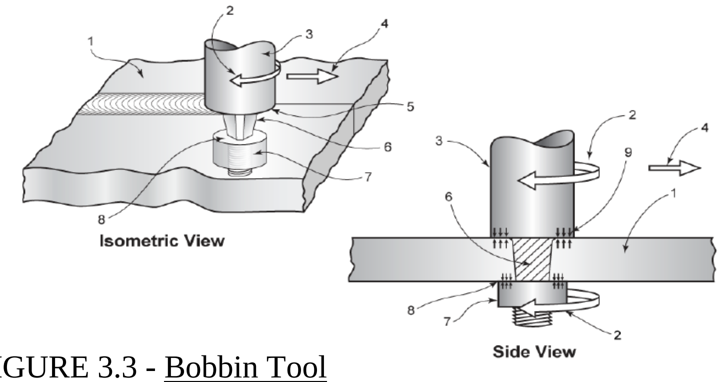
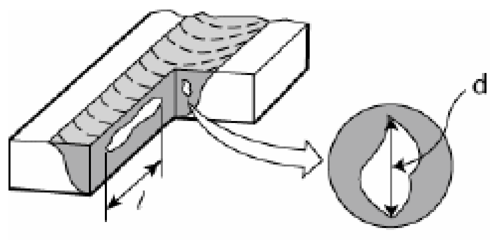


FIGURE 3.3 - Bobbin Tool

3.6 Cavity. A void-type discontinuity within a solid-state weld. See Figure 3.4.



Key

d Maximum transverse cross-sectional dimension of the cavity
l Length of a cavity in the longitudinal direction of the weld

FIGURE 3.4 - Cavity

3.7 Complex weld joint. A continuous weld joint with variations in section thickness and/or tapered thickness transitioning.

3.8 Direction of tool rotation. The rotation as viewed from the spindle that is rotating the tool. See Figure 3.1.

3.9 Dwell time at end of weld. The time interval after travel has stopped but before the rotating tool has begun to withdraw from the weld.

3.10 Dwell time at start of weld. The time interval between when the rotating tool reaches its maximum depth in the parent material and the start of travel.

3.11 Engineering Authority. The contracting agency or corporate organization that acts for and in behalf of the Customer on all matters within the scope of this standard. The Engineering Authority has the responsibility for the structural integrity or maintenance of airworthiness of the hardware and compliance with all contract documents.

3.12 Engineering drawing. Technical information, given on an information carrier, presented graphically in accordance with agreed rules and usually to scale.

3.13 Entrance block. A sacrificial piece of metal that is secured to the beginning of a FSW joint, and provides filler material as the tool enters the edge of a workpiece.

3.14 Exit hole. The depression located at the weld termination point which remains after the withdrawal of the tool. See Figure 3.1.

3.15 Exit block. A sacrificial piece of metal that is secured to the end of a FSW joint, and by providing filler material, eliminates an exit hole in the weldment. The exit hole will be relocated to the exit block.

3.16 Contractor. A person or organization that is responsible for production welding.

3.17 Faying surface. The surface of one component which is intended to be in contact with, or in close proximity to the surface of another component to form a joint.

3.18 Fixed pin. A fixed length pin protruding from the shoulder and the pin's rotation is the same as the shoulder during welding.

3.19 Flash. Material expelled along the weld toe during FSW. See Figure 3.5.

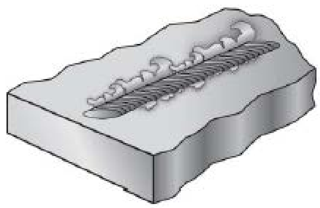


FIGURE 3.5 - Toe Flash

3.20 Force control. A method to maintain the required force on the tool during welding.

3.21 Friction stir welding. A material joining process where two or more metal workpieces are joined by the friction heating and mixing of material in the plastic state caused by a rotating tool that traverses along the weld. See Figures 3.1 and 3.6.

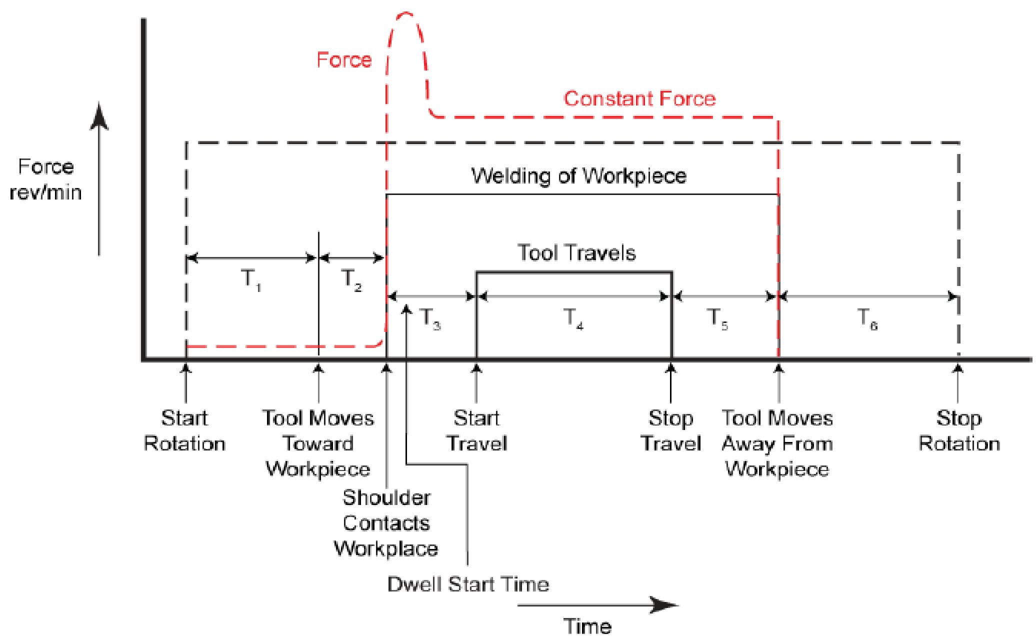


FIGURE 3.6 – Graph of FSW Process

3.22 Friction stir welding methods. Methods include, but are not limited to, robotic, single spindle, multiple spindles, self-reacting tool, and simultaneous two-sided welding.

3.23 Friction stir welding operator. A person who performs fully mechanized or automatic friction stir welding.

3.24 Heat affected zone (HAZ). The area of weld joint which has had its microstructure and properties altered by the heat of a welding process.

3.25 Heel. Part of the tool shoulder that is at the rear of the tool relative to its forward motion. See Figure 3.7.

3.26 Heel plunge depth. Distance the heel extends into the workpiece. See Figure 3.7.

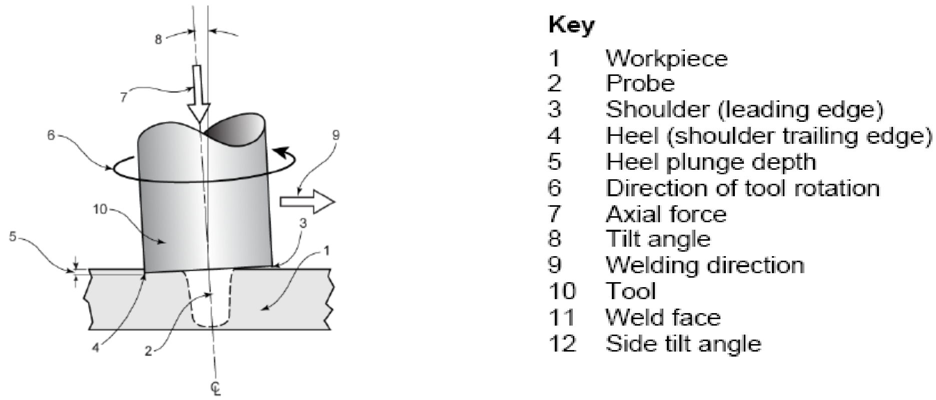


FIGURE 3.7 – Heel Plunge Depth

3.27 Hook. Faying surface that curves upward or downward along the side of the weld metal in a friction stir welded lap joint. See Figure 3.8.

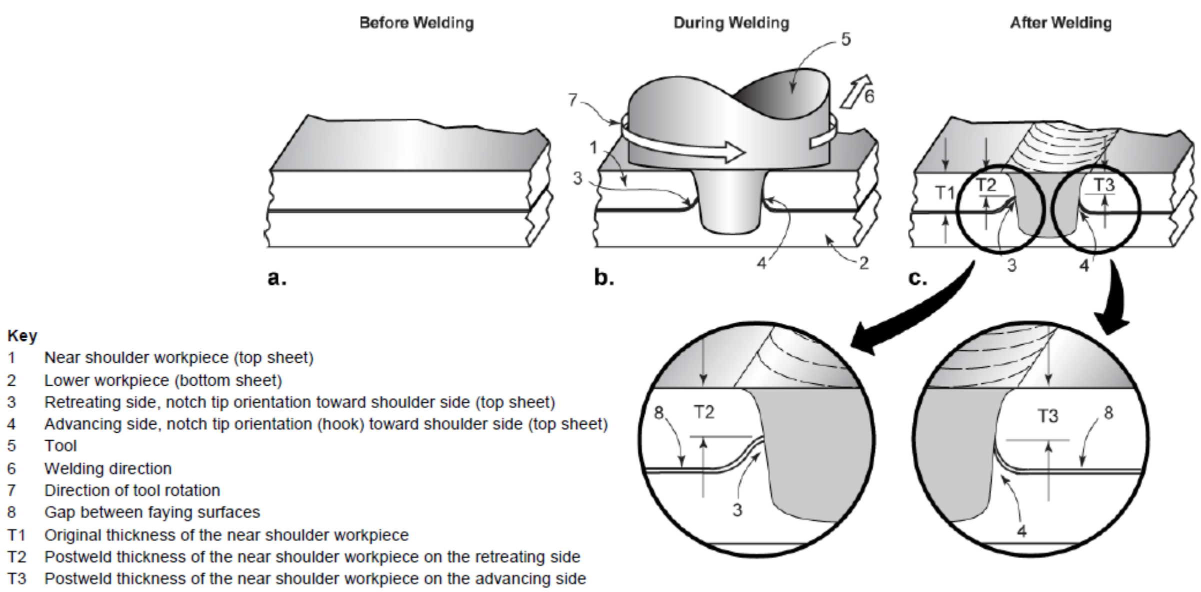


FIGURE 3.8 – Hook in a Lap Weld

3.28 Hole plug. A piece of filler metal which has been machined to allow its insertion into a hole and will be joined to the structure by FSW.

3.29 Incomplete joint penetration. A weld discontinuity where the full thickness of the joint has not been welded. See Figure 3.9.

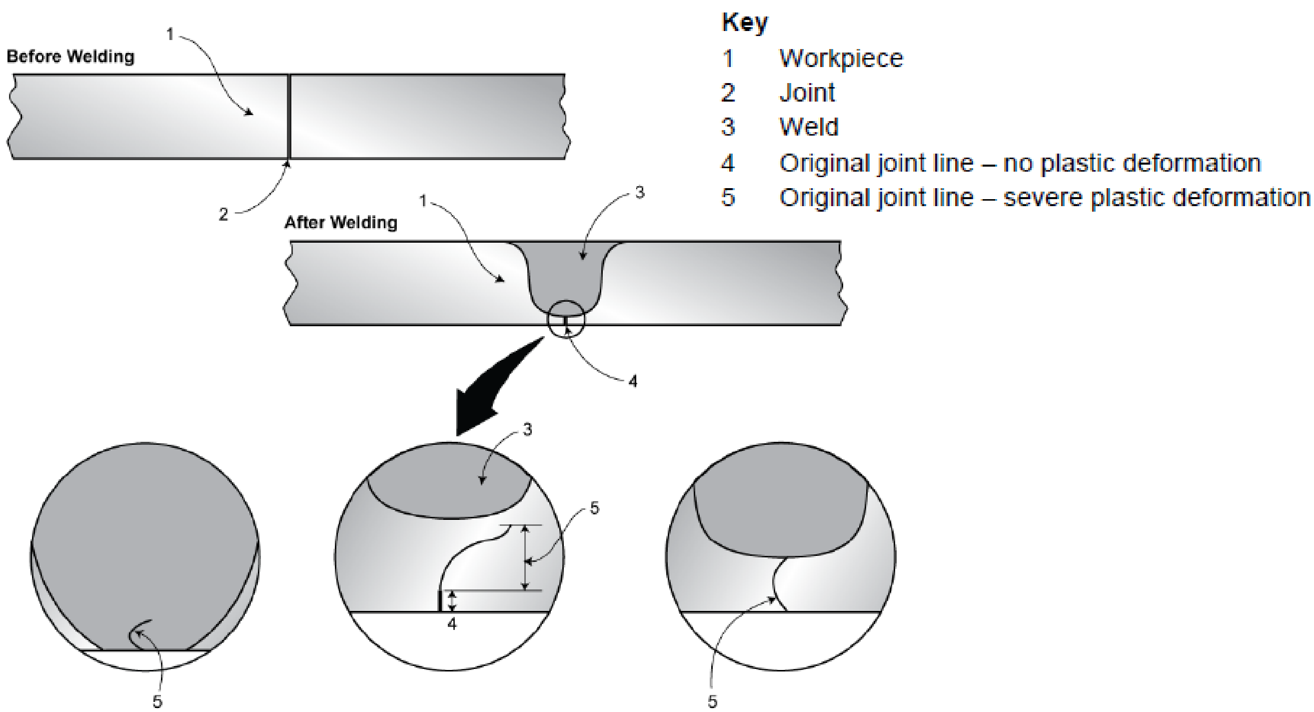


FIGURE 3.9 – Incomplete Joint Penetration

3.30 Lateral offset. The distance from the tool axis to the faying surface. See Figure 3.10.

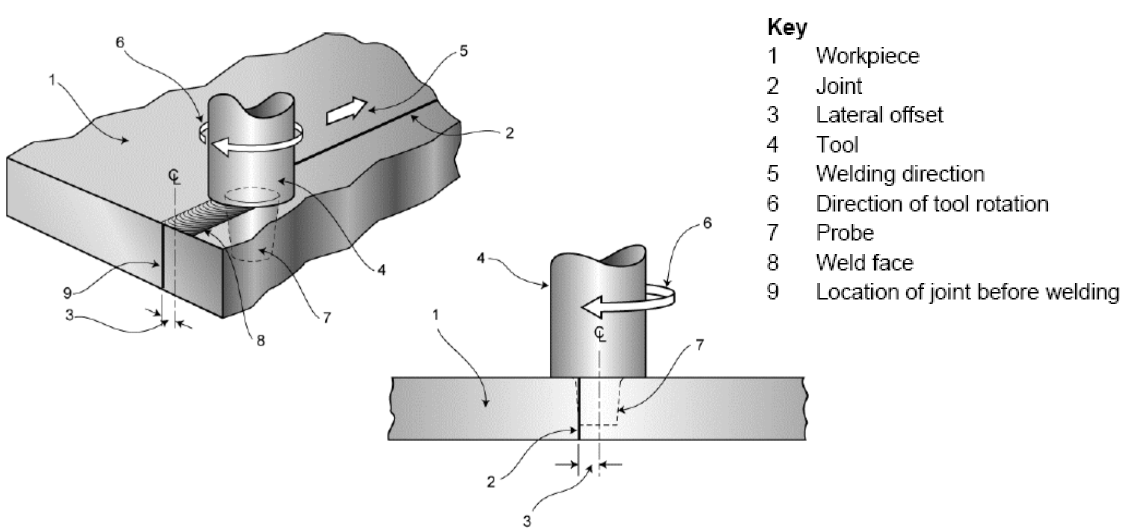


FIGURE 3.10 – Lateral Offset

3.31 Linear mismatch across joint. Misalignment between two welded pieces such that while their surface planes are parallel, they are not in the required plane. See Figure 3.11.

Key
T nominal thickness of the base metal
h height of mismatch

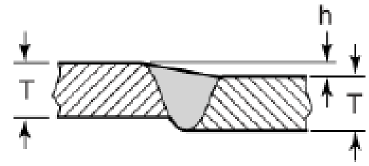


FIGURE 3.11 – Linear Mismatch

3.32 Multi-run welding. Welding in which the weld is made in more than one run.

3.33 Multiple spindles. A friction stir welding system with two or more spindles.

3.34 Pin. Part of the welding tool that extends into the workpiece to make the weld. See Figure 3.12. . *NOTE: The pin can be either fixed or adjustable.*

3.35 Pipe. Tube in standardized combination of outside diameter and wall thickness. *NOTE: In this standard, the term pipe will be used for pipe and tube.*

3.36 Plasticity .The softening of metal material before it reaches its melting point. The mechanism usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature.

3.37 Plate. Rolled, extruded, cast, forged, or deposited products other than pipe in thickness greater than 0.006 inches [0.152 mm]. NOTE: In this standard, the term plate is being used to describe all metal products, other than pipe.

3.38 Position control. A method to maintain the required position of the tool during welding.

3.39 Preliminary Welding Procedure Specification (pWPS). A document containing the required variables of a qualified welding procedure.

3.40 Pre-production test. A Welding test having the same function as a welding procedure test, but based on a non-standard test piece representative of the production conditions.

3.41 Procedure qualification variable. Controllable detail, which, if changed beyond the limitations of the welding procedure specification, requires re-qualification of the WPS.

3.42 Production sample test. Testing of actual welded products sampled from a continuous production.

3.43 Referencing Document. A fabrication code, specification, contract document, or internal document, such as the engineering drawing, quality control or quality assurance manuals that invokes this specification.

3.44 Retreating side of weld. Side of the weld where the direction of tool rotation is opposite to the welding direction. See Figure 3.1.

3.45 Self-reacting tool. A tool with two shoulders separated by a fixed length probe or an adjustable-length probe. Also see 3.5, Bobbin Tool.

3.46 Shoulder. The portion of the tool contacting the surface of the parent material during welding. See Figure 3.7.

3.47 Side tilt angle. The angle between the tool's axis and an axis normal to the base material surface, measured in a plane perpendicular to the weld path.

3.48 Single run welding. Welding in which the weld is made in one run.

3.49 Single spindle. A friction stir welding system with one spindle.

3.50 Standard welding test. Welding and testing of a standardized test piece in order to qualify a welding operator.

3.51 Stirred zone. The oval shaped region in the center of the weld, where a fine-grained, equated microstructure exists.

3.52 Test piece. A weldment used for testing purposes.

3.53 Test specimen. Portion cut from a test piece in order to perform a specified destructive test.

3.54 Test specimen blank. Portion of a test piece removed for the production of a destructive test specimen. *NOTE: In some cases, the test specimen blank is also the test specimen.*

3.55 Thermo-mechanically affected zone (TMAZ). The area of weld joint that has been plastically deformed by the tool and has also had its microstructure and properties altered by the heat of a welding process.

3.56 Tilt angle. The angle between the tool's axis and a plane perpendicular to the weld path, when viewed perpendicular to the weld path.

3.57 Tool (friction stir welding). A FSW tool is the rotating component that includes the shoulder and pin. See Figure 3.12. Generally, as base material thickness is increased, the shoulder diameter and pin length are also increased. Various pin designs include, but are not limited to, threaded, scrolled, fluted, or smooth. Pins may also have adjustable length and, with a special spindle, counter-rotating. *NOTE- A tool usually has a shoulder and a pin, but a tool may have more than one shoulder or more than one pin. Also, a tool may not have a shoulder or a pin.*

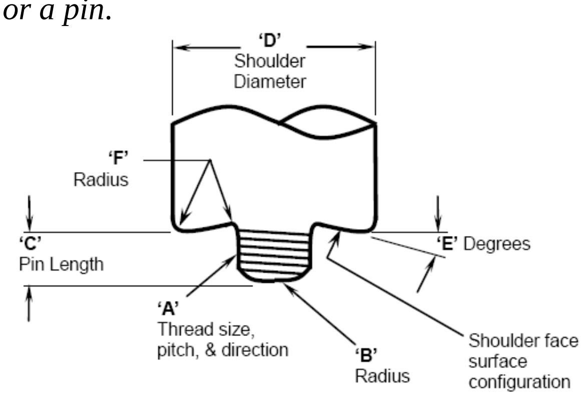


FIGURE 3.12 - FSW Tool

3.58 Tool rotation speed. Angular speed of the welding tool in revolutions per minute.

3.59 Travel speed. Rate at which the welding operation progresses in the direction of welding.

3.60 Tube. Hollow, wrought product that is long in relation to its cross section, which is symmetrical and is round, elliptical, a regular hexagon or octagon, or square or rectangular with sharp or rounded corners, and has uniform wall thickness except as affected by corner radii.

3.61 Underfill. A depression resulting when the weld face is below the adjacent parent material surface. See Figure 3.13. *NOTE - This is a common characteristic of the friction stir welding process.*

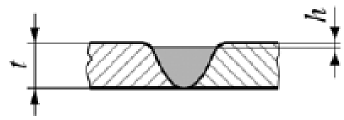


FIGURE 3.13 - Underfill

3.62 Weld overlap area (WOA). The area where the end of the weld overlaps the start of the weld. *NOTE - A WOA is common during pipe welding.*

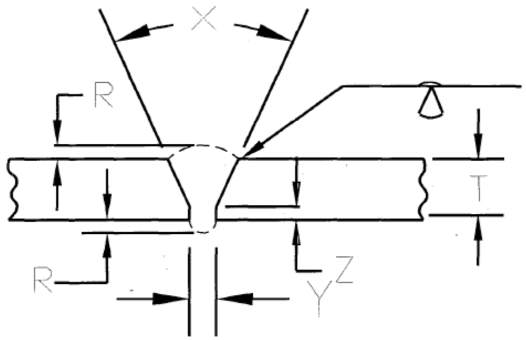
3.63 Welding Procedure Specification (WPS). A document that has been qualified and provides the required variables of the welding procedure to ensure repeatability during production welding.

3.64 Welding Procedure Qualification Record (WPQR). The WPQR is a statement of the test results of each test specimen.

APPENDIX B

Design Characteristics of Ballistic Weld Joints – FSW vs. Fusion Welding

APPENDIX B



Joint No.	Included Angle (d) X (Degrees)	Design Opening (a) Y (millimeters)	Root Face Z (millimeters)	Max Plate Thickness T (millimeters)	Reinforcement of Weld R (millimeters)	Depth of Bevel (millimeters)
1A	45	(b) 1.6	(c) 0	19.1	2.4	T

NOTES:

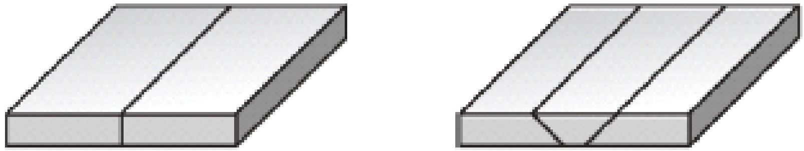
(a) Design openings (see "Y" in fig. 1) do not include allowance for shrinkage during welding.

(b) Tolerance, plus 4.8, minus 0 millimeters.

(c) Tolerance, plus 1.6, minus 0 millimeters.

(d) Tolerance, plus 10, minus 0 degrees.

FIGURE 1. Type 1. Single-v-grooved butt joint, welded both sides.



Fusion weld joint (MIL-HDBK-21)

Equivalent FSW joint (AWS or ISO)

Type I – Single V-Grooved Butt Joint

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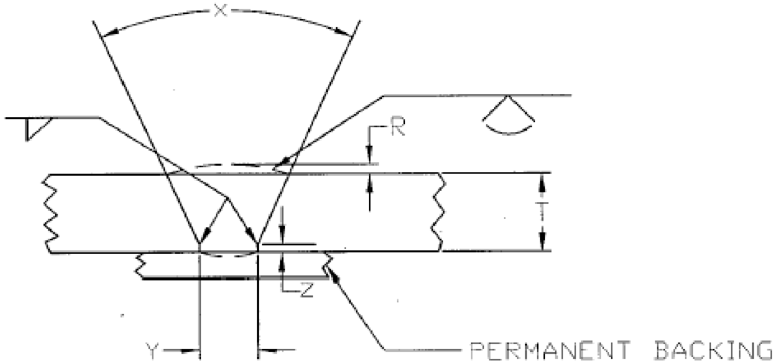
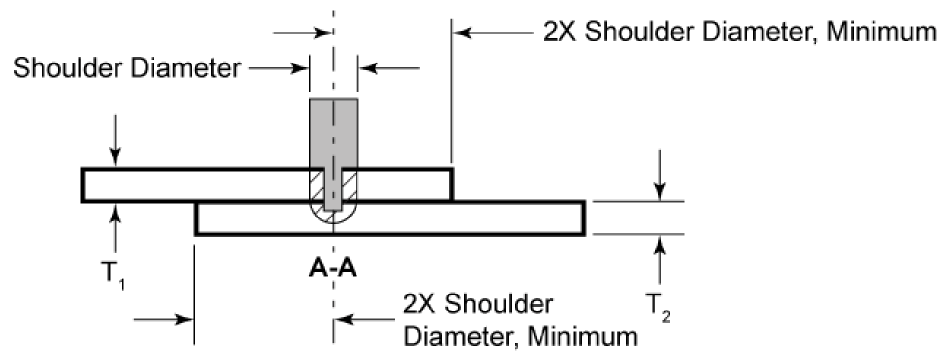


Jint No. (a)	Included Angle (e) X (Degrees)	Design Opening (b) Y (millimeters)	Root Face Z (millimeters)	Max Plate Thickness T (millimeters)	of Weld (millimeters)	Depth of Bevel (millimeters)
2A	45	12.7 (c)	(d) 0	19.1	0 to 2.4	T

NOTES:

(a) To be used only where it is impossible to weld backside of joint.
(b) Design openings (see "Y" in fig. 2) do not include allowance for shrinkage during welding.
(c) Tolerance, plus 4.8 minus 0 millimeters.
(d) Tolerance. plus 1.6 minus 0 millimeters.
(e) Tolerance, plus 10, minus 0 degrees.

FIGURE 2. Type 2. Single-v-grooved butt joint, welding to backing.

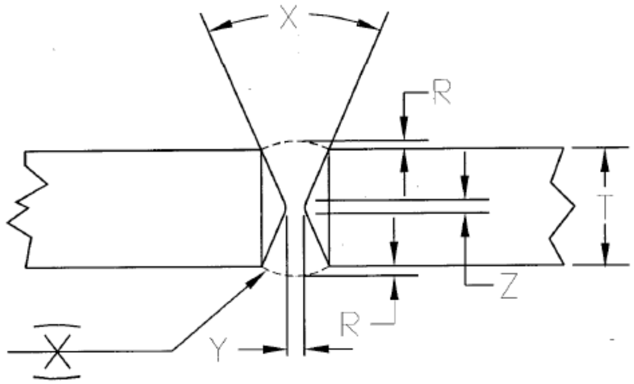


Fusion weld joint (MIL-HDBK-21)

Equivalent FSW joint (AWS or ISO)

Type 2 – Single V-Grooved Butt Joint with Backing

APPENDIX B

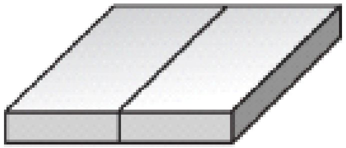


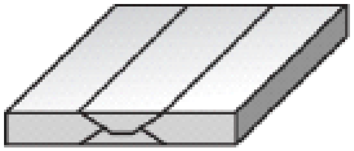
Joint No. (a)	Included Angle (e) X (Degrees)	Design Opening (a) Y (millimeter)	Root Face Z (millimeters)	Reinforcement of Weld R (millimeters)	Depth of Bevel (millimeters)
3A	45	(b) 4.8	(c) 0	0 to 2.4	12.7 T
3B	45	(b) 6.4	(c) 0	0 to 2.4	12.7 T
3C	45	(b) 7.9	(c) 1.6	0 to 2.4	12.7 T

NOTES:

(a) Design openings (see "Y" in fig. 3) do not include allowances for shrinkage during welding.
(b) Tolerance, plus 4.8, minus 0 millimeters.
(c) Tolerance, plus 1.6 minus 0 millimeters.
(d) Tolerance, plus or minus 1.6 millimeters.
(e) Tolerance, plus 10, minus 0 degrees.

FIGURE 3. Type 3. Double-v-grooved butt joint, welded both sides.



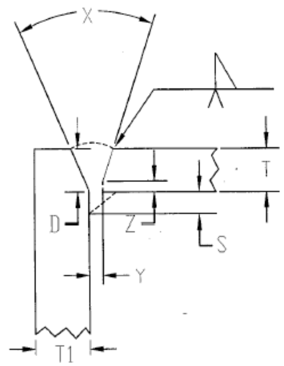


Fusion weld joint (MIL-HDBK-21)

Equivalent FSW joint (AWS or ISO)

Type 3 – Double V-Grooved Butt Joint

APPENDIX B

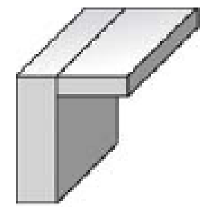


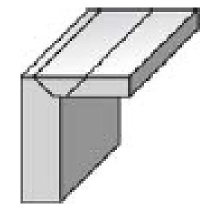
Joint No.	Included Angle (e) X (Degrees)	Design Opening (a) Y (millimeters)	Root Face Z (millimeters)	Plate Thickness T (millimeters)	Plate Thickness T1 (millimeters)	Depth of Bevel D (millimeters)	Min Size of Fillet S (millimeters)
4A	45	(b) 4.8	(c) 0 to	6.4	(d)	T	4.8
4B	45	(b) 4.8	(c) 0 to	9.5 to 12.7	(d)	T	6.4
4C	45	(b) 4.8	(c) 0 to	15.9 to 19.1	(d)	T	7.9

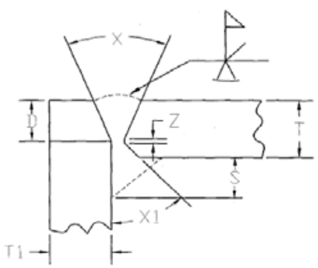
NOTES:

(a) Design openings (see "Y" in fig. 4) do not include allowance for shrinkage during welding.
(b) Tolerance, plus 4.8, minus 0 millimeters.
(c) Tolerance, plus 1.6, minus 0 millimeters.
(d) Values to be equal to or greater than for T-plate thickness.
(e) Tolerance, plus 10, minus 0 degrees.

FIGURE 4. Type 4. Single-v-grooved corner joint, fillet-reinforced.





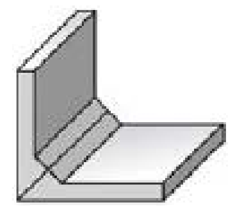


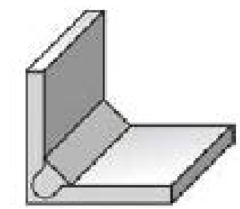
Joint No.	Min Included Angle (f) X (Outside) (Degrees)	Min Included Angle X1 (Inside) (Degrees)	Design Opening (a) Y (millimeter)	Root Face Z (millimeter)	Plate Thickness T (millimeter)	Plate Thickness T1 (millimeter)	Depth of Bevel D (millimeter)	Min. Size of Fillet S (millimeter)
6A	45	45	(b) 4.8	(c) 0	9.5 to 12.7	(c)	16.9 to 19.1T	6.4
6B	45	45	(b) 4.8	(c) 0	15.9 to 19.1	(e)	16.9 to 19.1T	7.9
6C	45	45	(b) 6.4	(c) 0	25.4	(e)	16.9 to 19.1T	15.9
6D	45	45	(b) 6.4	(c) 0	6.4	(e)	12.7 to 16.9T	11.1
6E	45	45	(b) 6.4	(c) 0	38.1	(e)	12.7 to 16.9T	12.7
6F	45	45	(b) 9.5	(c) 0	greater than 38.1	(e)	12.7 to 16.9T	12.7

FIGURE 6. Type 6. Double-bevel-grooved corner joint, fillet-reinforced.

(b) Tolerance, plus 4.8, minus 0 millimeters.
(c) Tolerance, plus 1.6, minus 0 millimeters.
(d) Tolerance, plus 1.6, minus 0 millimeters.
(e) Thickness for each joint to be equal to or greater than its T-plate thickness.
(f) Tolerance, plus 10 minus 0 degrees.

FIGURE 6. Type 6. Double-bevel-grooved corner joint, fillet-reinforced - Continued.

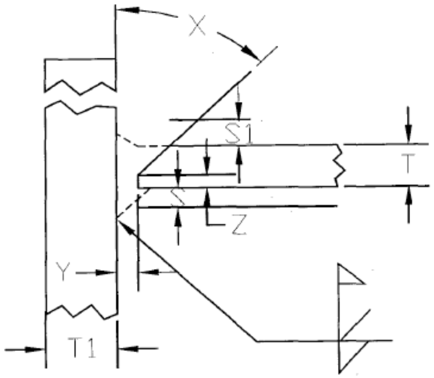




Fusion weld joint (MIL-HDBK-21) Equivalent FSW joint (AWS or ISO)

Types 4 & 6 – Corner Joints

APPENDIX B

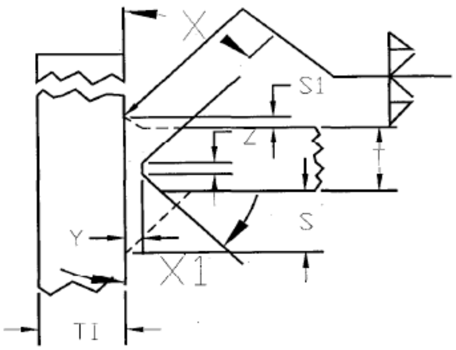


Joint No.	Included Angle (e) X (Degrees)	Design Opening (a) Y (millimeters)	Root Face Z (millimeters)	Plate Thickness T (millimeters)	Plate Thickness T1 (millimeters)	Depth of Bevel (millimeters)	Min Size of Fillet S (millimeters)	Min Size of Fillet S1 (millimeters)
5A	45	(b) 4.8	(c) 0 to 3.2	6.4	(d)	T	4.8	6.4
5B	45	(b) 4.8	(c) 0 to 3.2	9.5	(d)	T	6.4	6.4
5C	45	(b) 4.8	(c) 0 to 3.2	12.7	(d)	T	7.9	6.4
5D	45	(b) 4.8	(c) 0 to 3.2	15.9	(d)	T	9.5	6.4
5E	45	(b) 4.8	(c) 0 to 3.2	19.1	(d)	T	12.7	6.4

NOTES:

(a) Design openings (see "Y" in fig. 5) do not include allowances for shrinkage during welding.
(b) Tolerance, plus 4.8, minus 0 millimeters.
(c) Tolerance, plus 1.6, minus 0 millimeters.
(d) Values to be equal or greater than for T-plate thickness.
(e) Tolerance, plus 10, minus 0 degrees.

FIGURE 5. Type 5. Single-bevel-grooved corner joint, double-fillet reinforced.

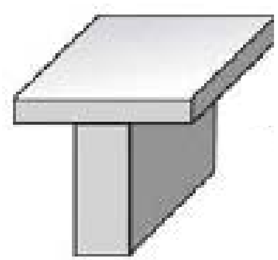


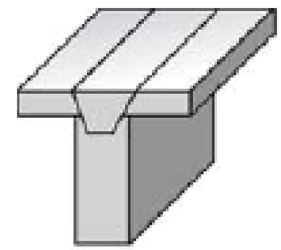
Joint No.	Included Angle X (f) (Outside) (Deg)	Included Angle X1 (Inside) (Deg)	Design Opening (a) Y (millimeter)	Root Face Z (millimeter)	Plate Thickness T (millimeter)	Plate Thickness T1 (millimeter)	Depth of Bevel (millimeter)	Min Size of Fillet S (millimeter)	Min Size of Fillet S1 (millimeter)
7A	45	45	(b) 4.8	(c) 0	9.5	(e)	12.7 to 16.9	6.4	6.4
7B	45	45	(b) 4.8	(c) 0	12.7	(e)	12.7 to 16.9	7.9	6.4
7C	45	45	(b) 4.8	(c) 0	15.9	(e)	12.7 to 16.9	9.5	6.4
7D	45	45	(b) 4.8	(c) 0	19.1	(e)	12.7 to 16.9	12.7	6.4
7E	45	45	(b) 6.4	(c) 0	25.4	(e)	12.7 to 16.9	15.9	7.9
7F	45	45	(b) 6.4	(c) 0	31.8	(e)	12.7 to 16.9	19.1	7.9
7G	45	45	(b) 6.4	(c) 0	38.1	(a)	12.7 to 16.9	22.2	7.9
7H	45	45	(b) 7.9	(c) 1.6	Greater than 38.1	(e)	12.7 to 16.9	22.2	7.9

NOTES:

(a) Design openings (see "Y" in fig. 7) do not include allowance for shrinkage during welding.
(b) Tolerance, plus 4.8, minus 0 millimeters.
(c) Tolerance, plus 1.6, minus 0 millimeters.
(d) Tolerance, plus 1.6, minus 0 millimeters.
(e) Thickness for each joint to be equal to or greater than its T-plate thickness.
(f) Tolerance, plus 10 minus 0 degrees.

FIGURE 7. Type 7. Double-bevel-grooved tee or corner joint, double-fillet-reinforced.



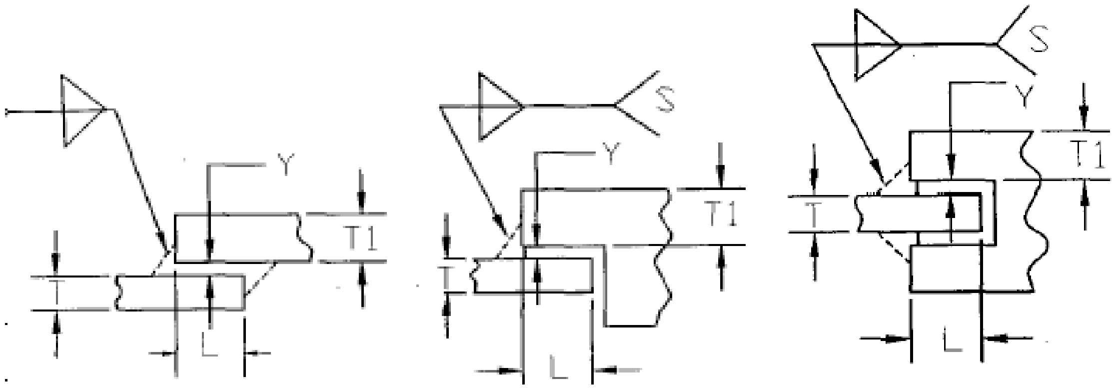


Fusion weld joint (MIL-HDBK-21)

Equivalent FSW joint (AWS or ISO)

Types 5 & 7 – T –Joints

APPENDIX B



Joint No.	Plate Thickness T	Minimum Flange Thickness T1	Minimum Flange Lap L	Minimum Fillet Size S
10A	less than 9.5	T	6.4	4.8
10B	9.5 to 15.9 incl	T	7.9	7.9
10C	15.9 to 25.4 incl	T	9.5	12.7
10D	25.4 to 38.1 incl	T	12.7	22.2
10E	greater than 38.1	T	15.9	25.4

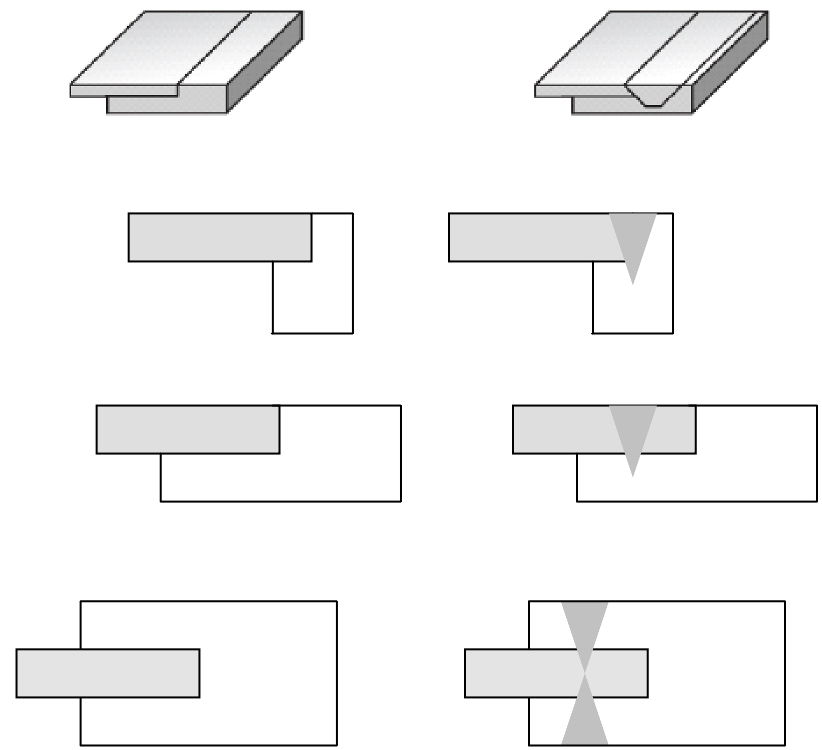
NOTE:

(a) Separation. ("Y") when specified shall not exceed 81.3 mm, and furthermore:

When Y = 40.6 mm or less, S = designed fillet size;
When Y = 2.4 to 3.2 mm, S = Y plus designed fillet size.

(b) This joint type is not to be utilized without prior approval from the procuring agency at which time layouts will be reviewed showing the circumstances under which the joint is to be employed. The circumstances under which this joint is to be employed should be analyzed very carefully by the designer to assure that it will not be misused. This joint is not intended to add mechanical strength to the structure nor is it considered a ballistic joint; therefore, should not be utilized in cases where it is depended upon to perform such functions.

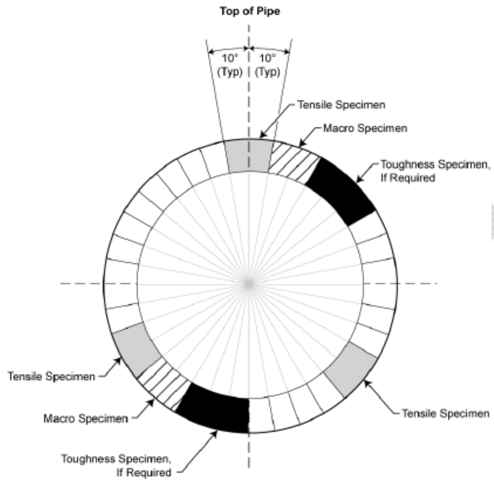
FIGURE 10. Type 10. Continuous-fillet-welded joint with mechanical reinforcement.



Fusion weld joint (MIL-HDBK-21) | Equivalent FSW joint (AWS or ISO)

Type 10 – Joints with Mechanical Reinforcement

APPENDIX C
FSW Test Weld Geometry *(From AWS D17.3)*

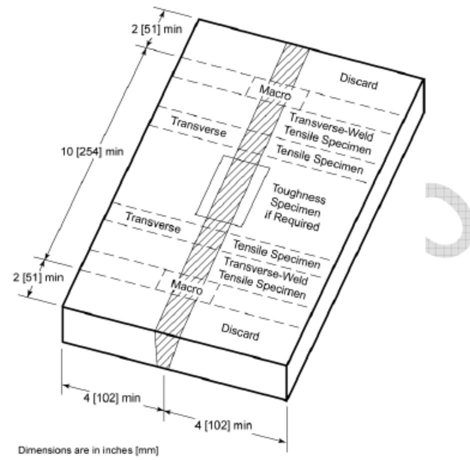


Note: The angular measurements are approximate

General Notes:
- The base metal thickness shall be determined in accordance with 6.7.2(1).
- The dimensions for test specimen blanks and details are given in Annex A.

Source: Adapted from AWS B2.1:2000, *Specification for Welding Procedure and Performance Qualification*, Figure 2.2.

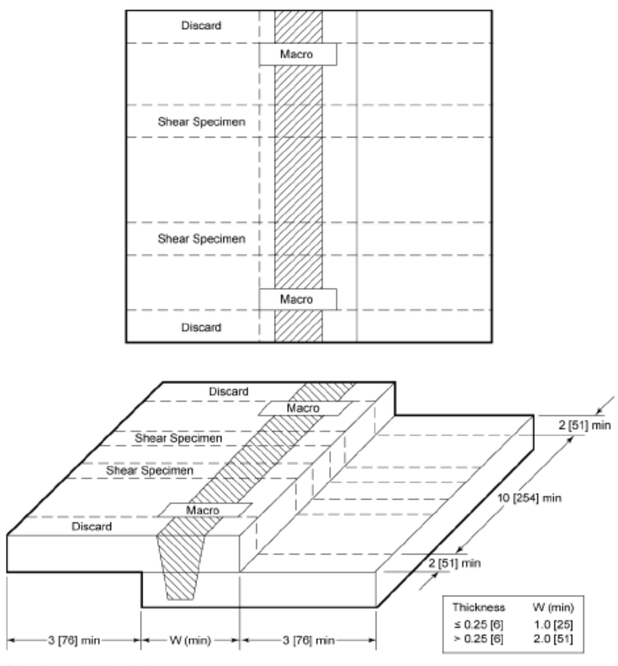
Figure 6.2— Location of Square Groove Weld Test Specimens—Pipe



General Notes:
- The base metal thickness shall be determined in accordance with 6.7.2(1).
- The dimensions for test specimen blanks and details are given in Annex A.
- The test plate length shall be sufficient for the required number and type of specimens.

Source: Adapted from AWS B2.1:2000 *Specification for Welding Procedure and Performance Qualification*, Figure 2.5.

Figure 6.3—Location of Square Groove Weld Test Specimens—Plate



General Notes:
- The base metal thickness shall be determined in accordance with 6.7.2(1).
- The dimensions for test specimen blanks and details are given in Annex A.
- The test plate length shall be sufficient for the required number and type of specimens.

Figure 6.5—Location of Seam Weld Test Specimens—Plate

APPENDIX D

Ballistic Armor Materials