NASA/TM—2012–217474

Effects of Fusion Tack Welds on Self-Reacting Friction Stir Welds

A.C. Nunes, Jr., M.L. Pendleton, S.A. Brooke, and C.K. Russell
Marshall Space Flight Center, Huntsville, Alabama

November 2012

The NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>

- E-mail your question via the Internet to <help@sti.nasa.gov>

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Phone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2012–217474

Effects of Fusion Tack Welds on Self-Reacting Friction Stir Welds

A.C. Nunes, Jr., M.L. Pendleton, S.A. Brooke, and C.K. Russell
Marshall Space Flight Center, Huntsville, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

November 2012

TRADEMARKS

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076–1320
443–757–5802

This report is also available in electronic form at
<https://www2.sti.nasa.gov/login/wt/>

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND DESIGNATORS

DCEN	direct current electrode negative (arc welding mode)
FSW	friction stir welding
FTA01, FTA02, etc.	test panel designations (0.327 in thick)
GTA	gas tungsten arc
GTAW	gas tungsten arc welding
GTA01, GTA02, etc.	test panel designations (0.257 in thick)
SRFSW	self-reacting friction stir welding

NOMENCLATURE

a	position independent constant in linear representation of nontack-containing coupon fracture stress within a given panel
a_T	position independent constant in linear representation of tack-containing coupon fracture stress within a given panel
b	position slope constant in linear representation of nontack-containing coupon fracture stress within a given panel
b_T	position slope constant in linear representation of tack-containing coupon fracture stress within a given panel
N	number of data items in a sample
$\bar{X}$	mean of sample measurements
x	position from end of panel where friction stir weld begins
x_i	mean position from end of panel where friction stir weld begins of ith fracture test coupon in a given panel; test measurement datum
$\Delta\sigma_T$	interpolated difference between fracture stress of tack-containing and nontack-containing fracture test coupons in a given panel, i.e., $\sigma_T - \sigma$, measure of the effect of a tack weld on a given panel
$\Delta\sigma_T/\sigma$	interpolated difference between fracture stress of tack-containing and nontack-containing fracture test coupons in a given panel, a measure of the effect of a tack weld on a given panel, normalized with respect to interpolated fracture stress for both test coupons not containing a tack weld in a given panel
ε	sum of squares of errors, differences between estimated measure and actual measure
μ	mean of population of measurements
σ	interpolated fracture stress for both test coupons not containing a tack weld in a given panel; standard deviation of population of measurements
σ_i	fracture stress of ith fracture test coupon in a given panel
σ_T	interpolated fracture stress for all four test coupons containing a tack weld in a given panel

TECHNICAL MEMORANDUM

EFFECTS OF FUSION TACK WELDS ON SELF-REACTING FRICTION STIR WELDS

1. INTRODUCTION

This Technical Memorandum is based on a report submitted to the Metals Joining and Processes Branch, Materials and Processes Laboratory, Marshall Space Flight Center, July 29, 2011, by M.L. Pendleton, Professional Intern Program, and S.A. Brookes entitled “A Study of the Effects of Autogenous Gas Tungsten Fusion Tacking of Self-Reacting Friction Stir Welds.”

It is standard welding practice to join the edges of a weld seam at an array of points along the seam prior to welding to prevent slippage and misalignment during welding. The initially joined points are called ‘tack welds.’ Tack welds are not necessarily produced by the same welding process as welding the seam.

The friction stir welding (FSW) process was originally introduced at Marshall Space Flight Center for fabrication of a lightweight version of the space shuttle external tank out of a new alloy that proved difficult to weld by fusion processes. FSW is a solid state process in which a rotating pin is inserted into the weld seam and literally stirs the sides of the seam together as it is translated along the seam. The initial version of the FSW process required a large axial compression force on the tool, which had to be balanced by a heavy anvil incorporated into the weld fixture. A later version of the FSW process eliminated this large axial force by splitting the tool in two and pulling crown and root shoulders together so as to balance the axial compression within the tool and substitute a squeeze for an unbalanced axial force. This was the self-reacting friction stir welding (SRFSW) process, now in common use for welding light alloy aerospace structures.

The SRFSW process has not yet been adapted to the production of tack welds. Tack welds can currently be made by the old FSW process, which requires heavy fixtures, or by fusion welding, which does not require heavy fixtures.

The belief that the tack weld will be swallowed up by the FSW process with no effect upon the resulting weld led to the idea to use the much more convenient fusion tack weld process rather than the old FSW process. But caution required verification of this belief. Tack welds do not usually penetrate fully through the seam; they are only supposed to hold the seam together under limited loading, and if this purpose is fulfilled, the smaller the weld, the better. It was thought conceivable that the residual parts of the weld seam near enough to the tack weld to reach a high temperature but not incorporated into the tack weld might be oxidized to an extent that the seam trace would be weakened (residual oxide defect) and the weld strength reduced.

The object of the present study was to see if a tack weld effect could be detected by comparison of the strengths of weld segments cut from fusion tack welded regions with segments cut from outside the tack welds. An array of different autogenous (i.e., no filler-wire supplement) gas tungsten arc (GTA) tack weld schedules and different FSW process conditions (panel thickness, time elapsed after cleaning, pin-tool offset from the seam) were evaluated to obtain a comprehensive grasp of the situation. Nondestructive evaluation (NDE) and metallographic microstructural observations supplemented measurements of weld strengths.

Upon completion of this study, no effect of a fusion tack weld on the strength of a friction stir-welded seam weld was detected.

2. PROCEDURE

2.1 Panels

The welds in this study were made on pairs of 6-in × 24-in 2195 aluminum alloy panels in the T8M4 condition. Thicknesses were either 0.257 or 0.327 in. The panels were welded by the SRFSW process along the long side to produce panels 12 in × 24 in with a weld down the center to be evaluated.

2.2 Gas Tungsten Arc Tack Weld Surface Preparation

The top and bottom surfaces adjacent to the weld seam were cleaned with Scotch-Brite™ or a wire brush to a distance at least 1.5 in from the seam. The surface was wiped with acetone (followed by isopropyl alcohol when using Scotch-Brite). The abutting surfaces were draw filed or scraped. The panels were handled throughout with clean gloves to avoid contamination with skin oils. During storage the panels were wrapped in brown paper and kept free of dust and contamination.

2.3 Gas Tungsten Arc Tack Weld Parameters

Hot, nominal, and cold tack weld parameters were defined based upon the penetration depth of the tack weld into the weld seam. A 30% penetration was deemed a hot weld; 20% penetration, a nominal weld; and 10% penetration, a cold weld.

GTA weld parameters necessary to achieve the above penetrations in the experimental panels were determined by trial and error. Gas tungsten arc welding (GTAW) as used for tack welding is a manual and not an automated process. Constant current power sources are typically used for GTAW. The current is set as a parameter, and the voltage (and power) is determined by the arc length held by the welder. By observing the weld pool, the welder can estimate the depth of penetration, which can be adjusted by lengthening or shortening the arc. Weld speed can also affect penetration but is not as sensitive as arc length. In this study, manual tack welding speed is taken as roughly constant, about 15 in/min. The GTA parameter determined here amounts to weld current setting. The current settings established are listed in table 1 for the 0.327-in-thick panels and in table 2 for the 0.257-in panels. Voltages ranged from 12 to 14 V. These parameters were used to tack weld the test panels.

Table 1. Parameters for GTA tack welds.

	Panel Thickness (in)	
	0.257	0.327
	Current Settings (A)	
Hot	120	160
Nominal	113	140
Cold	105	120

Table 2. Nominal FSW parameters.

Panel Thickness (in)	Tool Rotational Speed (rpm)	Weld Speed (in/min)	Pinch Force (lb)
0.257	225	15	2,400
0.327	150	15	4,000

The GTA torch was operated in the direct current electrode negative (DCEN) mode. In the DCEN mode, heating action is maximized and there is no reverse polarity surface cleaning effect.

2.4 Gas Tungsten Arc Tack Weld Panel Configuration

The tack welds were applied in the following order:

(1) A 2-in tack weld was applied on each end of the seam to be welded.

(2) A pair of 4-in tack welds separated by three, 4-in untacked intervals filled in the 20-in weld segment between the end tack welds. The resultant placement of tack welds on a panel is illustrated in figure 1.

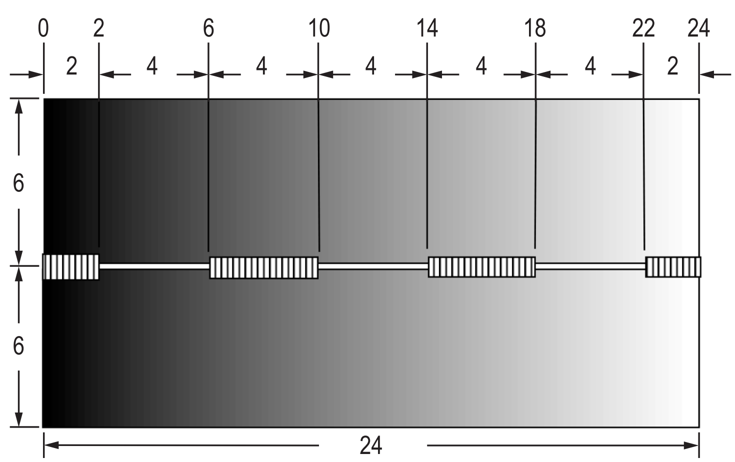

Figure 1. GTA tack weld panel configuration (dimensions in inches).

2.5 Delay Intervals

Because of the possibility that delay intervals between preparation and tacking or between tacking and friction stir welding might give time for detrimental reactions between the weld seam and the environment, a delay interval parameter was introduced into the study. One set of panels was prepared, tacked, and friction stir welded the same day (prep/tack/FSW); another set was welded with a 5-day delay between preparation and tacking and another 5-day delay between tacking and friction stir welding (prep/5 days/tack/5 days/FSW).

2.6 Friction Stir Weld Welding Parameters

Referring to figure 1 at a distance of 1.5 in, a 0.516-in- (33/64) diameter hole was drilled in the panel, either on the weld seam or displaced 0.06 in downwards, i.e., toward the retreating side of a clockwise-rotating pin-tool moving to the right so that the pin encounters the seam displaced toward its advancing side. Two pin-tool offsets were used in this study: 0 and 0.06 in.

The nominal weld parameters are listed in table 2.

Although the same parameters are used to weld both thicknesses, the machine torque—not recorded—will be greater in the case of the thicker panel.

2.7 Test Matrix

Table 3 shows the 24 panels that were tested: 2 thicknesses $\times$ 3 tack weld parameters $\times$ 2 delay intervals $\times$ 2 FSW offsets.

2.8 Mechanical Testing Procedures

Welds were evaluated by tensile tests of 1.1-in-wide coupons stressed perpendicular to the weld direction. Six coupons from each panel were cut as shown in figure 2 and tested, yielding $24 \times 6 = 144$ tensile test data tabulated in the appendix. It can be seen in figure 2 that four of the coupons on each panel enclose tack welds; two do not.

2.9 Nondestructive Evaluation Procedures

After welding, but prior to cutting test coupons, the panels were inspected using phased array ultrasonic techniques. No defects were detected in the welds. The results of ultrasonic testing are presented in the Pendleton/Brooke report.

2.10 Metallographic Procedures

Four metallographic samples placed on the panels as shown in figure 3 were cut. Weld transverse sections were ground, polished, and etched and photographs of the weld macrostructure were taken.

Table 3. Test matrix.

Panel Thickness (in)	GTA Tack Heat Level	Delay	Seam Offset Toward Advancing Side (in)	Panel Designation
0.257	Hot	Prep/tack/FSW	–	GTA01
			0.06	GTA04
		Prep/5 days/tack/ 5 days/FSW	–	GTA07
			0.06	GTA10
	Nominal	Prep/tack/FSW	–	GTA02
			0.06	GTA05
		Prep/5 days/tack/ 5 days/FSW	–	GTA08
			0.06	GTA11
	Cold	Prep/tack/FSW	–	GTA03
			0.06	GTA06
		Prep/5 days/tack/ 5 days/FSW	–	GTA09
			0.06	GTA12
0.327	Hot	Prep/tack/FSW	–	FTA01
			0.06	FTA04
		Prep/5 days/tack/ 5 days/FSW	–	FTA07
			0.06	FTA10
	Nominal	Prep/tack/FSW	–	FTA02
			0.06	FTA05
		Prep/5 days/tack/ 5 days/FSW	–	FTA08
			0.06	FTA11
	Cold	Prep/tack/FSW	–	FTA03
			0.06	FTA06
		Prep/5 days/tack/ 5 days/FSW	–	FTA09
			0.06	FTA12

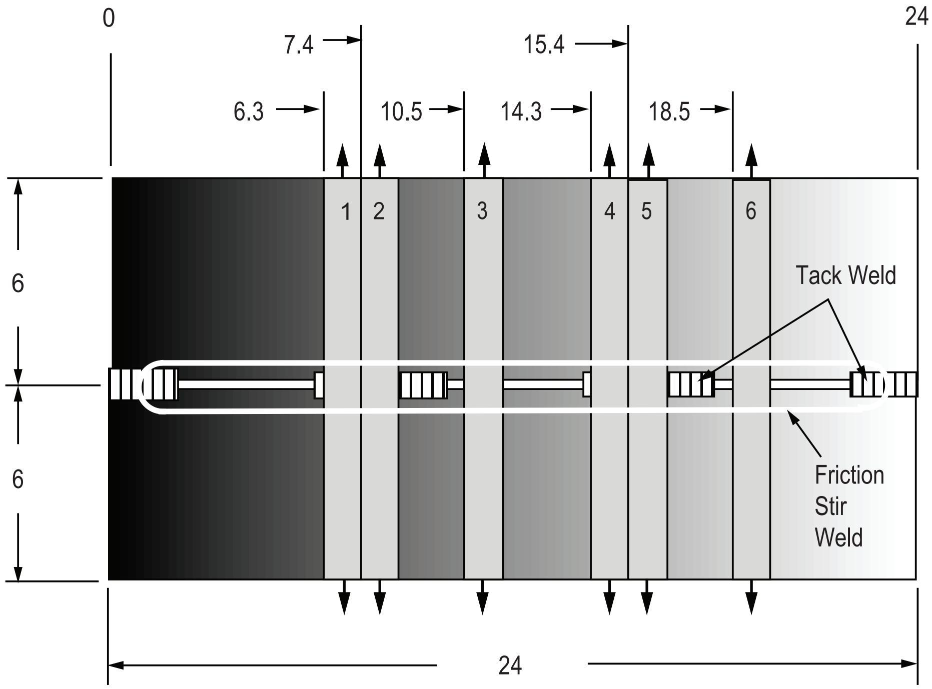

Figure 2. Location of tensile test coupons on panel (dimensions in inches).

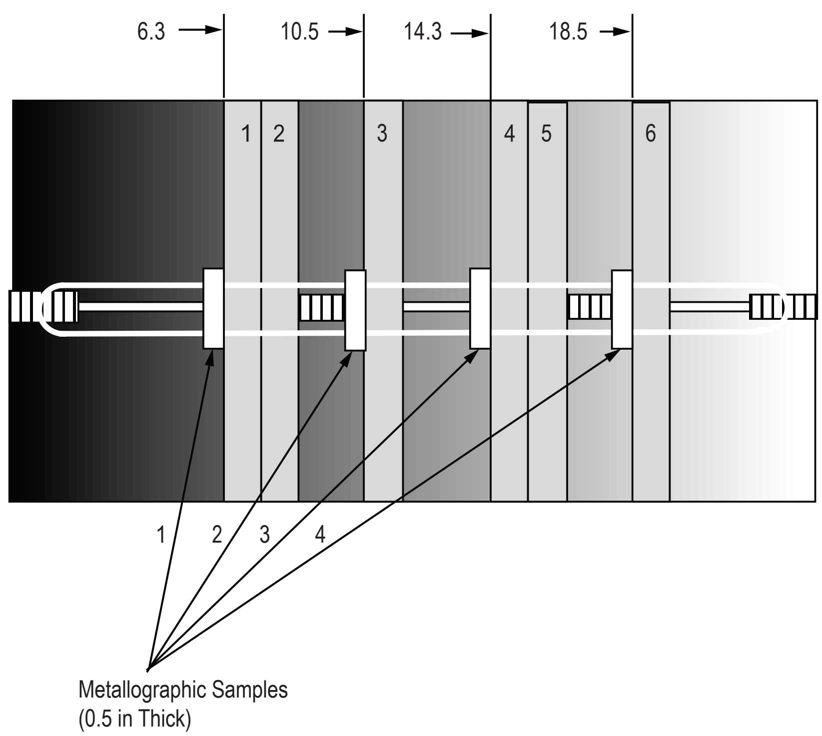

Figure 3. Placement of metallographic specimens on weld panels (dimensions in inches).

Transverse structures of weld FTA03 (0.327 inches thick panel, cold weld parameters, prep/tack/FSW with no delay, no seam offset) at the M1 (incorporating a tack weld) and M2 (not incorporating a tack weld) positions are shown in figure 4 and figure 5 respectively.

Figure 4. Transverse section of panel FTA03 (0.327 inches thick panel, cold weld parameters, prep/tack/FSW with no delay, no seam offset) at the M1 (incorporating a tack weld) position.

Figure 5. Transverse section of panel FTA03 (0.327 inches thick panel, cold weld parameters, prep/tack/FSW with no delay, no seam offset) at the M2 (not incorporating a tack weld) position.

The weld structure may be interpreted as follows.

Stuck to the friction stir pin and shoulder is a rotating plug of metal separated from the nonrotating weld metal by a shear surface with contours selected by nature to allow the tool to rotate with minimal torque. For a self-reacting tool, the shear surface takes an hour-glass shape, narrow at the pin midpoint and widening toward the shoulders. The width at the shoulder will, in general, be less than that of the tool shoulder by the amount of slippage taking place at the outer edge of the tool shoulder. Hour-glass asymmetry along the pin axis is associated with temperature asymmetry. If the shoulder on the crown side is colder than that on the root side, the crown side shear stress should be higher; a higher shear stress makes it easier for slip to occur (in preference to shear), and a relatively smaller crown side hour-glass diameter would be anticipated.

Weld metal encountering this shear surface is highly deformed at the forward surface so as to take a fine-grained structure, rotated to the rear surface, and abandoned to the wake of the weld. Thus, the basic structure observed on the transverse weld section is a fine-grained, hour-glass shape with top and bottom (root and crown) approaching the width of the shoulder and middle somewhat wider than the pin.

Pin threads and shoulder scrolls induce a gradual rotation in the weld metal flow along the tool axis toward the middle of the pin, then outward and around and back toward the pin at the tool shoulders. This (ring vortex) flow distorts the hour-glass shape, bulging it out at the middle of the pin and retracting it closer to the shoulders.

Eccentricity of the tool pumps metal back and forth along hot, soft-metal channels following the shear surface so as to produce internal textural bands and surface ripples customarily called ‘tool marks.’ In the transverse weld section of a traditional friction stir weld, these bands appear as the ‘onion ring’ pattern. In the transverse weld section of a self-reacting weld, the middle bulge of the hour-glass shape is not as pronounced and the bands appear as a series of hyperbolas in the crown and root expansions of the hour-glass shape.

3. ANALYSIS OF DATA

3.1 A Measure of Tack Weld Effect

An analysis is only as good as the concepts upon which it is based. Here, the concepts on which the present analysis of data rests will be made clear, and based on these concepts, a quantitative measure of the effect of a tack weld will be established.

First, weld segments incorporating a tack weld (coupons 1, 2, 4, and 5) and segments not incorporating a tack weld (coupons 3 and 6) may be distinguished. Other things being equal, the 'effect of a tack weld' is taken as the difference in fracture strength of a coupon containing a tack weld and one not containing a tack weld. If the tack weld is detrimental, this effect is negative.

But other things are not equal, so it will be necessary to attempt to estimate and eliminate the effect of 'other things' for purposes of extracting the effect of a tack weld.

Within each panel, a monotonic weld strength variation is anticipated due to the gradual heating of the panel, a periodic variation due to local heat sink variations as each hold-down clamp is bypassed and a chaotic variation due to local variations in weld metal past processing and weld fit-up and cleaning. For present purposes, only an attempt to compensate for monotonic variations will be made, and an error band due to the other or further overlooked causes of variation will be anticipated. The error band will manifest itself as multiple data are collected.

Within a given panel, it is anticipated that the fracture stress, σ, is a function of the position along the panel, x. This function will be approximated by the simplest function the data will bear, a straight line. Data from tack-containing coupons is labeled with a subscript T.

For the coupons containing a tack weld,

$$\sigma_T = a_T + b_T x \quad . \tag{1}$$

For the coupons not containing a tack weld,

$$\sigma = a + bx \quad . \tag{2}$$

The effect of the tack weld is $\Delta\sigma_T$, such that

$$\Delta\sigma_T = \sigma_T - \sigma = (a_T - a) + (b_T - b)x \quad . \tag{3}$$

$\Delta\sigma_T$ captures the effect of tack welds on a single panel including a first-order variation with position. This is illustrated in figure 6.

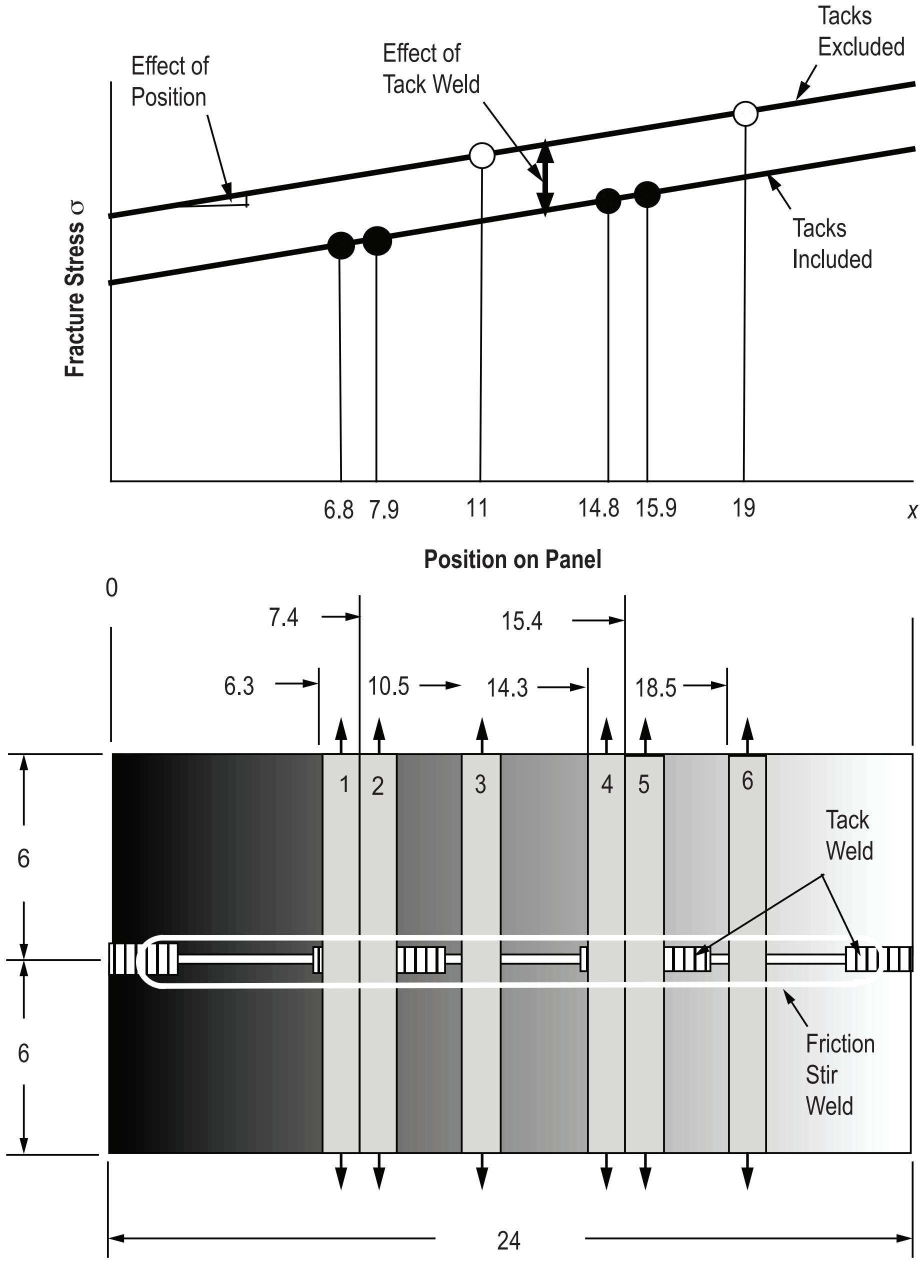

Figure 6. Idealized determination of tack weld effect.

The effect of tack welds is anticipated to vary not only along panels but also from panel to panel. Normalizing the measurement with respect to the strength for individual panels, $\Delta\sigma_T/\sigma$, can reduce obscuring of the tack weld effect caused by panel-to-panel variation:

$$\frac{\Delta\sigma_T}{\sigma} = \frac{\left(a_T - a\right) + \left(b_T - b\right)x}{a + bx} \ . \tag{4}$$

The estimates of σ_T and σ can be obtained from a least-squares data fit. The least-squares error, ε, is determined by:

$$\varepsilon \equiv \sum_i \left(a + bx_i - \sigma_i\right)^2 \ , \tag{5}$$

$$\frac{\partial\varepsilon}{\partial a} = 2\sum_i \left(a + bx_i - \sigma_i\right) = 2\left(aN + b\sum_i x_i - \sum_i \sigma_i \right) = 0 \ , \tag{6}$$

$$\frac{\partial\varepsilon}{\partial b} = 2\sum_i \left(a + bx_i - \sigma_i\right)x_i = 2\left(a\sum_i x_i + b\sum_i x_i^2 - \sum_i \sigma_i x_i \right) = 0 \ , \tag{7}$$

$$a = \frac{\dfrac{\sum_i \sigma_i}{N} - \dfrac{\sum_i \sigma_i x_i \sum_i x_i}{N\sum_i x_i^2}}{1 - \dfrac{\left(\sum_i x_i\right)^2}{N\sum_i x_i^2}} \ , \tag{8}$$

and

$$b = \frac{\dfrac{\sum_i \sigma_i}{\sum_i x_i} - \dfrac{N\sum_i \sigma_i x_i}{\left(\sum_i x_i\right)^2}}{1 - \dfrac{N\sum_i x_i^2}{\left(\sum_i x_i\right)^2}} \ . \tag{9}$$

For this particular experiment a measure of tack weld effect for a particular panel can be obtained by evaluating the quantities in equations (8) and (9). For coupons 3 and 6 not containing the tack welds:

$$a = \frac{\dfrac{(\sigma_3+\sigma_6)}{2} - \dfrac{(11\sigma_3+19\sigma_6)(11+19)}{2\left(11^2+19^2\right)}}{1-\dfrac{(11+19)^2}{2\left(11^2+19^2\right)}} = \frac{19}{8}\sigma_3 - \frac{11}{8}\sigma_6 = 2.375\sigma_3 - 1.375\sigma_6 \tag{10}$$

and

$$b = \frac{\dfrac{(\sigma_3+\sigma_6)}{(11+19)} - \dfrac{2(11\sigma_3+19\sigma_6)}{(11+19)^2}}{1-\dfrac{2\left(11^2+19^2\right)}{(11+19)^2}} = \frac{\sigma_6-\sigma_3}{8} = 0.125(\sigma_6-\sigma_3)\ . \tag{11}$$

For coupons 1, 2, 4, and 5 containing the tack welds,

$$a_T = \frac{\dfrac{(\sigma_1+\sigma_2+\sigma_4+\sigma_5)}{4} - \dfrac{(6.8\sigma_1+7.9\sigma_2+14.8\sigma_4+15.9\sigma_5)(6.8+7.9+14.8+15.9)}{4\left(6.8^2+7.9^2+14.8^2+15.9^2\right)}}{1-\dfrac{(6.8+7.9+14.8+15.9)^2}{4\left(6.8^2+7.9^2+14.8^2+15.9^2\right)}}$$

$$= 1.042\sigma_1 + 0.85\sigma_2 - 0.35\sigma_4 - 0.542\sigma_5 \tag{12}$$

and

$$b_T = \frac{\dfrac{(\sigma_1+\sigma_2+\sigma_4+\sigma_5)}{(6.8+7.9+14.8+15.9)} - \dfrac{4(6.8\sigma_1+7.9\sigma_2+14.8\sigma_4+15.9\sigma_5)}{(6.8+7.9+14.8+15.9)^2}}{1-\dfrac{4\left(6.8^2+7.9^2+14.8^2+15.9^2\right)}{(6.8+7.9+14.8+15.9)^2}}$$

$$= -0.0698\sigma_1 - 0.0529\sigma_2 - 0.0529\sigma_4 + 0.0698\sigma_5. \tag{13}$$

Note that for a single value of fracture stress, $\sigma_i = \sigma$, the slope, b, is zero and the value of the least-squares fit is the constant $a = \sigma$; hence, the a-coefficients of the stresses must sum to 1 and the b-coefficients must sum to zero. This property of the expressions for a and b provides a quick check on the computation. The condition is satisfied in expressions (10)–(13).

3.2 Results

From fracture stresses of the individual coupons tabulated in table 5 in the appendix, the measure of the tack weld effect for each of the 24 weld panels was computed using equations (4) and (10)–(13) and tabulated in table 4 on the following page.

Some (positive) measures show a strengthening effect correlated with an embedded tack weld. Some (negative) show a weakening tack weld effect.

The fusion weld effect in the thinner 0.257-in-thick GTA panels differs markedly from that in the thicker 0.327-in-thick FTA panels. Thick and thin panels will be considered separately.

Table 4. Analytical results of coupon tests.

Panel	Fracture Stress σ of Coupons Without Tack Weld (ksi) x = Position (in)	Fracture Stress σ_T of Coupons Tack Weld (ksi) x = Position (in)	Normalized Effect of Tack Weld $\frac{\sigma_T - \sigma}{\sigma}$	Tack Weld Effect: Median (x = 12) Range (x = 0) (x = 24)
GTA01	38.77 + 1.26x	59.02 – 0.24x	$\frac{0.52 - 0.04x}{1 + 0.03x}$	3% 52% –26%
GTA02	66.45 – 0.45x	62.97 + 0.1x	$\frac{-0.04 + 0.01x}{1 - 0.01x}$	9% –4% –26%
GTA03	56.89 + 0.37x	64.61 – 0.1x	$\frac{0.14 - 0.01x}{1 + 0.01x}$	2% 14% –8%
GTA04	63.38 + 0.08x	60.2 + 0.23x	$\frac{-0.05 - 0x}{1 + 0x} = -0.05$	–5%
GTA05	59.29 + 0.32x	66 – 0.23x	$\frac{0.11 - 0.01x}{1 + 0.01x}$	–1% 11% –10%
GTA06	64.54 + 0.02x	65.52–0.13x	$\frac{0.02 - 0x}{1 + 0x} = 0.02$	2%
GTA07	64.23 + 0.01x	61.78 + 0.18x	$\frac{-0.04 + 0x}{1 + 0x} = -0.04$	–4%
GTA08	63.04 + 0.1x	67.38 – 0.41x	$\frac{0.07 - 0.01x}{1 + 0x}$	–5% 7% –17%
GTA09	58.37 – 0.39x	72.1 – 1.04x	$\frac{0.24 - 0.01x}{1 - 0x}$	12% 24% 0%
GTA10	68.60 – 0.84x	58.99 – 0.42x	$\frac{-0.14 + 0.01x}{1 - 0.01x}$	–2% –14% 13%
GTA11	63.62 – 0.33x	66.22 – 0.61x	$\frac{0.04 - 0x}{1 - 0.00x} = 0.04$	4%
GTA12	60.05 + 0.25x	57 + 0.42x	$\frac{-0.05 + 0x}{1 + 0x} = -0.05$	–5%
FTA01	64.57 + 0x	64.02 + 0.01x	$\frac{-0.01 - 0x}{1 + 0x} = -0.01$	–1%
FTA02	63.15 + 0.06x	63.02 + 0.06x	$\frac{0 + 0x}{1 + 0x} = 0.00$	0%
FTA03	63.25 + 0.06x	63.43 + 0.05x	$\frac{0 - 0x}{1 + 0x} = 0.00$	0%
FTA04	62.41 + 0.13x	63.36 + 0.08x	$\frac{0.02 - 0x}{1 + 0x} = 0.02$	2%
FTA05	63.41 + 0.05	63.75 + 0.04x	$\frac{0.01 - 0x}{1 + 0x} = 0.01$	1%
FTA06	63.97 + 0.03x	63.69 + 0.06x	$\frac{0 + 0x}{1 + 0x} = 0.00$	0%
FTA07	63.16 + 0.08x	63.58 + 0.04x	$\frac{0 - 0x}{1 + 0x} = 0.01$	1%
FTA08	63.38 + 0.03x	64.3 –0.09x	$\frac{0.01 - 0x}{1 + 0.00x} = 0.01$	1%
FTA09	64.07 + 0.01x	63.5 + 0.04x	$\frac{-0.01 - 0x}{1 + 0x} = -0.01$	–1%
FTA10	62.40 + 0.12x	63.75 + 0.06x	$\frac{0.02 - 0x}{1 + 0x} = 0.02$	2%
FTA11	63.28 + 0.06x	63.79 + 0.02x	$\frac{0.01 - 0x}{1 + 0x} = 0.01$	1%
FTA12	63.97 + 0.07x	64.52 + 0.03x	$\frac{0.01 - 0x}{1 + 0x} = 0.01$	1%

3.3 Interpretation of Results

Scientific hypotheses can never be confirmed by experimental data, only rejected. The entire body of scientific knowledge comprises unrejected hypotheses. The more stringent the tests for rejecting a hypothesis, the more confidence that can be accorded to an unrejected hypothesis.

The methodology used here to evaluate the data is as follows. The hypothesis to be tested (the null hypothesis) is that there is no tack weld effect, i.e., that the mean value of the measure taken for the tack weld effect for the entire infinite population of all possible measurements is zero.

If the members of the population of measurements x_i are distributed in a normal distribution about a mean,

$$\mu = \lim_{N \to \infty} \left(\frac{\sum_{i=1}^{i=N} x_i}{N} \right) \tag{14}$$

with a standard deviation σ such that

$$\sigma^2 = \lim_{N \to \infty} \left(\frac{\sum_{i=1}^{i=N} \left(x_i - \mu \right)^2}{N} \right) , \tag{15}$$

then means of samples of size N are expected to be distributed about population mean μ with standard deviation $\sigma/\sqrt{N}$. As sample sizes approach the population size, their means converge to μ. Means of smaller samples show greater variation, and the variation of single measurements ($N=1$) becomes that of the population itself.

To test the hypothesis that tack welds produce no effect, it is assumed that for the population of all measurements of tack weld effect the mean is zero ($\mu = 0$). The standard deviation of the population is estimated from the data in the samples such that

$$\sigma \approx \sqrt{\frac{\sum_{i=1}^{i=N}\left(x_i - \bar{X}\right)^2}{N}} \quad , \tag{16}$$

where $\bar{X}$ is the sample mean such that

$$\bar{X} = \frac{\sum_{i=1}^{i=N} x_i}{N} \quad . \tag{17}$$

The hypothesis is maintained unrejected by the experiment (and can be accepted pending further study) if the sample mean $\bar{X}$ is sufficiently close to the hypothetical population mean, $\mu = 0$ in the present case, as not to be too improbable. What degree of improbability is cause for rejection of the hypothesis is a subjective matter. A common criterion for rejection of a hypothesis is a less than 1 chance in 20, less than a 5% chance, of the data being compatible with the hypothesis. This is said to be a test at a 5% level of significance. Given a normal distribution, the hypothesis rejection criterion in the present case is

$$-2 > \frac{\bar{X}}{\left(\frac{\sigma}{\sqrt{N}}\right)} > 2 \quad . \tag{18}$$

Twelve thicker (0.327 in thick) FTA sample panels exhibited a mean strengthening effect of 0.6% with a standard deviation of 1%. The standard deviation for the sample of thick panel welds can then be estimated at $1\%/\sqrt{12} = 0.3\%$. The sample mean lies $0.6/0.3 = 2$ units away from the hypothetical zero effect. To a 5% level of significance, the tack weld effect is just on the border for rejection. The hypothesis may be considered verified to a 5% level of significance, and rejected if more stringent, higher levels of significance are required.

Twelve thinner (0.257 in thick) GTA sample panels exhibited substantially greater variation in fracture stress for unknown reasons. Computations of the mean and standard variation of the fracture stress ranged from 6.8% and 17.5%, respectively, at $x = 0$ through 0.8% and 5.6%, respectively, at $x = 12$ to –6.8% and 11.6%, respectively, at $x = 24$. The significantly larger standard deviations at the end points are understandable for extrapolation sites; the interpolation site at $x = 12$ presents a substantially smaller standard deviation, is anticipated to be a better indicator of tack weld effect, and is taken as the tack weld effect indicator for the thinner panels. The sample standard deviation is estimated at $5.6\%/\sqrt{12} = 1.6\%$. The estimate of the population mean from the sample data lies at a distance $0.8/1.6 = 0.5$ from the zero tack effect hypothesis, well inside the acceptance level for a 5% level of significance.

Hence, to an approximate 5% level of significance, this study detects no detriment in weld fracture strength because of the inclusion of a fusion tack weld.

A more stringent test, say, demanding only an estimated 1 in 10 probability or less of the experimental results for rejection of the hypothesis, i.e., a 10% level of significance, would reject the hypothesis for $-1.6 > \bar{X}/(\sigma/\sqrt{N}) > 1.6$. The thinner GTA panels still easily confirm the hypothesis, but now the thicker FTA panels reject the hypothesis; however, hypothetical population means of $0.6\% \pm 0.5\%$ with a minimum of 0.1% would be acceptable to a 10% level of significance. This is a small effect, and it is a strengthening, not a weakening, effect.

The tack weld effect data were examined to see if there might be an effect of tack weld heat level, processing delay, or seam offset, but no obvious effect was found.

4. CONCLUSIONS

A measure of the effect of fusion tack welds embedded in friction stir welds in test panels was devised. Twelve thinner (0.257 in thick) and twelve thicker (0.327 in thick) panels were fusion tacked and friction stir welded under various conditions and a measure of the fusion weld effect was computed for each panel from the fracture stresses of six coupons cut from the panel, four containing a tack weld and two not containing a tack weld.

The hypothesis that the embedded fusion tack welds had no effect on weld fracture strength was confirmed to a level of significance of 5%.

The more stringent confirmation requirements of a 10% level of significance would reject the zero effect hypothesis for the thicker panels, but would not reject effects in the range of 0.6% ± 0.5%, indicating a slight strengthening effect.

It is concluded that for the range of panel thicknesses and welding practices tested, no detrimental effects are to be anticipated from embedded fusion tack welds.

APPENDIX—FRACTURE STRESSES AND LOCATIONS

Table 5 shows the panel/coupon for fracture stresses and locations.

Table 5. Fracture stresses (ksi) and fracture location (retreating side = R, nugget = N, and advancing side = A).

Panel	Coupon					
	1	2	3	4	5	6
GTA01	55.78 N	59.24 N	52.6 N	53.64 N	56.61 N	62.66 N
GTA02	63.69 N/A	63.62 N	61.54 N	65.27 R	63.89 A	57.97 A
GTA03	63.55 A	64.48 R	60.96 N	61.14 N	64.61 R	63.92 N
GTA04	63.71 R	59.83 A	64.29 A	63.53 A	64.22 A	64.95 R
GTA05	64.63 R	63.85 N	62.84 N	63.92 N	61.34 N	65.42 R
GTA06	64.44 N	64.65 N	64.77 R	64.47 R/N	62.75 N	64.94 R
GTA07	63.29 A	62.88 N	64.30 R/N	64.58 R	64.60 R/N	64.35 N/A
GTA08	64.20 R	64.20 R	64.14 R	64.33 R	58.25 N/A	64.94 R
GTA09	64.17 N/A	64.56 N	54.08 N	58.51 N/A	53.81 N	50.96 N
GTA10	60.13 N	58.72 N	59.36 N	65.09 N	56.81 N	52.64 N
GTA11	64.58 R/N	57.73 N	59.95 N	63.28 N/A	51.65 N	57.28 N
GTA12	63.64 R/N	56.00 N	62.76 N	64.23 R	63.53 N	64.73 R/N
FTA01	64.14 R	64.05 R	64.58 R	64.32 R	64.11 R	64.59 R
FTA02	63.19 R/N	63.74 R/N	63.82 R/N	63.90 R/N	63.91 R/N	64.31 R/N
FTA03	63.84 R	63.68 R/N	63.95 R/N	64.32 R/N	64.03 R/N	64.46 R/N
FTA04	63.95 R	63.87 R/N	63.88 R/N	64.53 R/N	64.53 R/N	64.95 R
FTA05	64.09 R/N	63.93 R/N	63.90 R/N	64.51 R	64.20 R/N	64.26 R
FTA06	64.09 R/N	64.09 R/N	64.34 R/N	64.85 R/N	64.33 R/N	64.61 R/N
FTA07	64.10 R/N	63.64 R/N	63.98 R/N	64.40 R	64.14 R/N	64.58 R/N
FTA08	63.82 R/N	63.54 R/N	63.75 R/N	61.69 N	63.87 R/N	64.02 R/N
FTA09	63.95 R/N	63.63 R/N	64.12 R/N	64.17 R/N	64.13 R/N	64.16 R/N
FTA10	64.22 R/N	63.85 R/N	63.76 R/N	64.46 R/N	64.36 R	64.75 R/N
FTA11	64.10 R/N	63.64 R/N	63.90 R/N	64.44 R/N	63.74 R	64.35 R
FTA12	64.85 R	64.54 R/N	64.74 R/N	65.25 R	64.72 N	65.30 R

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01–11–2012

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Effects of Fusion Tack Welds on Self-Reacting Friction Stir Welds

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.C. Nunes, Jr., M.L. Pendleton, S.A. Brooke, and C.K. Russell

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Huntsville, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–1350

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM—2012–217474

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 37
Availability: NASA CASI (443–757–5802)

13. SUPPLEMENTARY NOTES
Prepared by the Materials & Processing Laboratory, Engineering Directorate

14. ABSTRACT
In order to know whether fusion tack welds would affect the strength of self-reacting friction stir seam welds in 2195-T87 aluminum alloy, the fracture stresses of 144 tensile test coupons cut from 24 welded panels containing segments of friction stir welds were measured. Each of the panels was welded under unique processing conditions. A measure of the effect of the tack welds for each panel was devised. An analysis of the measures of the tack weld effect supported the hypothesis that fusion tack welds do not affect the strength of self-reacting friction stir welds to a 5% level of confidence.

15. SUBJECT TERMS
tack welds, friction stir welds, welding, metals joining, metals processing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	UU	36

19a. NAME OF RESPONSIBLE PERSON
STI Help Desk at email: help@sti.nasa.gov

19b. TELEPHONE NUMBER *(Include area code)*
STI Help Desk at: 443–757–5802

National Aeronautics and
Space Administration
IS20
George C. Marshall Space Flight Center
Huntsville, Alabama 35812