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Bobbin-Tool Friction-Stir Welding of Thick-Walled Aluminum Alloy Pressure Vessels

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by

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It was desired to assemble thick-walled Al alloy 2219 pressure vessels by bobbin-tool friction-stir welding. To develop the welding-process, mechanical-property, and fitness-for-service information to support this effort, extensive friction-stir welding-parameter studies were conducted on 2.5 cm. and 3.8 cm. thick 2219 Al alloy plate. Starting conditions of the plate were the fully-heat-treated (-T62) and in the annealed (-O) conditions. The former condition was chosen with the intent of using the welds in either the “as welded” condition or after a simple low-temperature aging treatment. Since preliminary stress-analyses showed that stresses in and near the welds would probably exceed the yield-strength of both “as welded” and welded and aged weld-joints, a post-weld solution-treatment, quenching, and aging treatment was also examined.

Once a suitable set of welding and post-weld heat-treatment parameters was established, the project divided into two parts. The first part concentrated on developing the necessary process information to be able to make defect-free friction-stir welds in 3.8 cm. thick Al alloy 2219 in the form of circumferential welds that would join two hemispherical forgings with a 102 cm. inside diameter. This necessitated going to a bobbin-tool welding-technique to simplify the tooling needed to react the large forces generated in friction-stir welding. The bobbin-tool technique was demonstrated on both flat-plates and plates that were bent to the curvature of the actual vessel. An additional issue was termination of the weld, i.e. closing out the hole left at the end of the weld by withdrawal of the friction-stir welding tool. This was accomplished by friction-plug welding a slightly-oversized Al alloy 2219 plug into the termination-hole, followed by machining the plug flush with both the inside and outside surfaces of the vessel.

The second part of the project involved demonstrating that the welds were fit for the intended service. This involved determining the room-temperature tensile and elastic-plastic fracture-toughness properties of the bobbin-tool friction-stir welds after a post-weld solution-treatment, quenching, and aging heat-treatment. These mechanical properties were used to conduct fracture-mechanics analyses to determine critical flaw sizes. Phased-array and conventional ultrasonic non-destructive examination was used to demonstrate that no flaws that match or exceed the calculated critical flaw-sizes exist in or near the friction-stir welds.

INTRODUCTION

Friction-stir-welding has been successfully demonstrated to produce near full-strength welds in many high-strength Al alloys (refs. 1-2). Lawrence Livermore National Laboratory and Advanced Joining Technologies, Inc. have formed a team for the design, development, and manufacturing of polymer-matrix composite over-wrapped Al alloy pressure-vessels intended for the containment of dynamic loads. Preliminary analyses showed that near yield-stress loads would be developed in vessels consisting of a spherical section with two cylindrical nozzles (figure 1).

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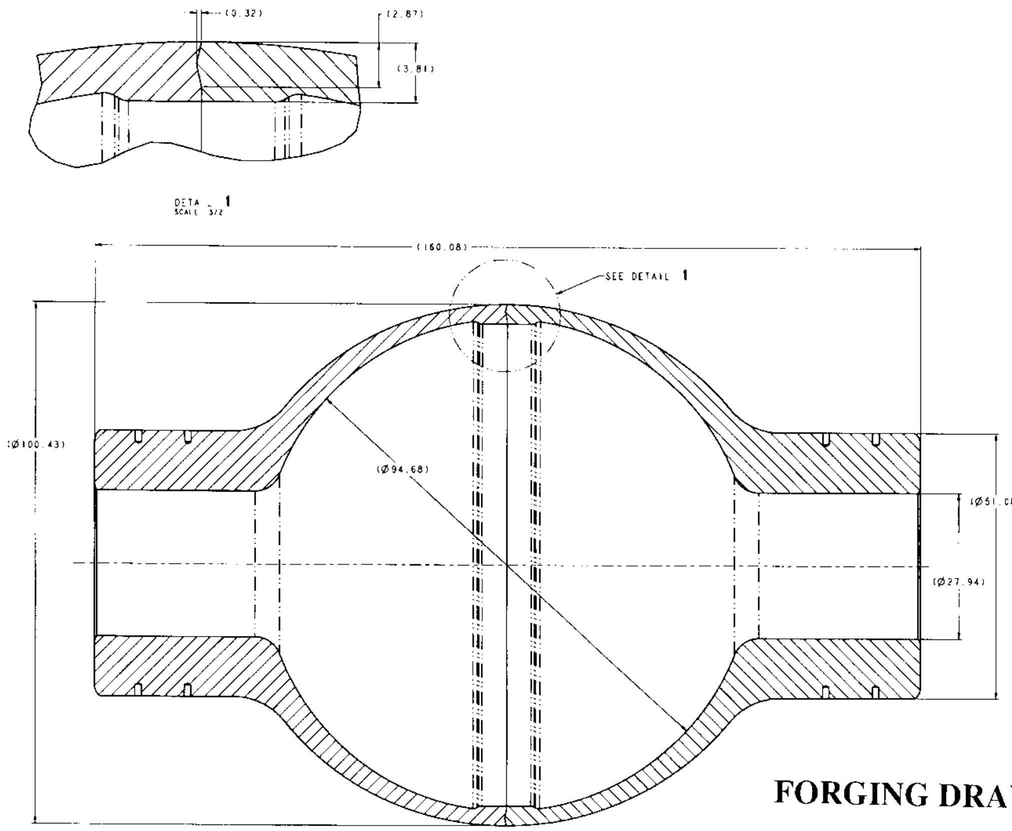


FORGING DRAWING

FIGURE ONE

Past experiences with fusion-welded Al alloy pressure vessels over-wrapped with polymer-matrix composites had shown that the defects inherent in fusion-welds in these alloys compromised the performance of otherwise useful developmental vessels (ref. 3). Consideration of the advantages of friction-stir welding, such as freedom from solidification-induced effects, improved fatigue-resistance over fusion-welded joints, good corrosion-resistance, and less distortion than for fusion-welded joints, was balanced against some drawbacks, such as difficulties in making “out of position” welds and a lack of information on completing welds that close on themselves, such as the circular weld that joins the two hemispheres in figure 1. After extensive discussions with organizations involved in friction-stir welding in the U.S.A. and the U.K. it was decided to work with Advanced Joining Technologies, Inc to develop the process-information, non-destructive examination (NDE) methods, and mechanical property data that would support the use of friction-stir welding to join the two hemispheres that would make up the vessel shown in figure 1.

DESIGN AND MATERIAL

Based on previous experience and extensive analyses, the shape of the vessel had evolved into that of a sphere, about 1 meter in inside diameter (ID),with a wall-thickness of 3.81 cm. This basic shape was modified by the addition of cylindrical nozzles at the top and bottom of the sphere for access to the interior of the vessel. Consultation with various Al alloy fabricators resulted in selection of the two modified spherical forgings (figure 2)

TWO 2219 ALUMINUM ALLOY FORGINGS

FIGURE TWO

that would be joined at their large open ends by a single-pass friction-stir weld. Given the need for a relatively high-strength at and near the weld, as well as some reservations about the availability of friction-stir welding job-shops, it was decided to use an Al alloy that was capable of being joined by the usual fusion-welding methods, should joining of thick (3.81 cm.) Al alloy forgings in the configuration shown in figure 1 prove difficult. The alloy chosen was alloy 2219, with a nominal composition of 5.8-6.8% Cu, 0.2-0.4% Mn, 0.10-0.25% Zr, with trace amounts of Ti, Si, Fe, Mg. and Zn. As forged and heat-treated to the artificially-aged or "-T62" condition, minimum room-temperature tensile properties are ultimate tensile strength of 400 MPA, 0.2% offset yield strength of 276 MPA and an elongation in 5.08 cm. of 6%, per ref. 4. Because there was no readilyavailable mechanical-property information on the properties of the friction-stir welds in alloy 2219, the forgings were purchased in the annealed condition, so that any combination of friction-stir welding and heat-treatment could be used, once development work was done.

FRICTION-STIR WELDING (FSW) DEVELOPMENT

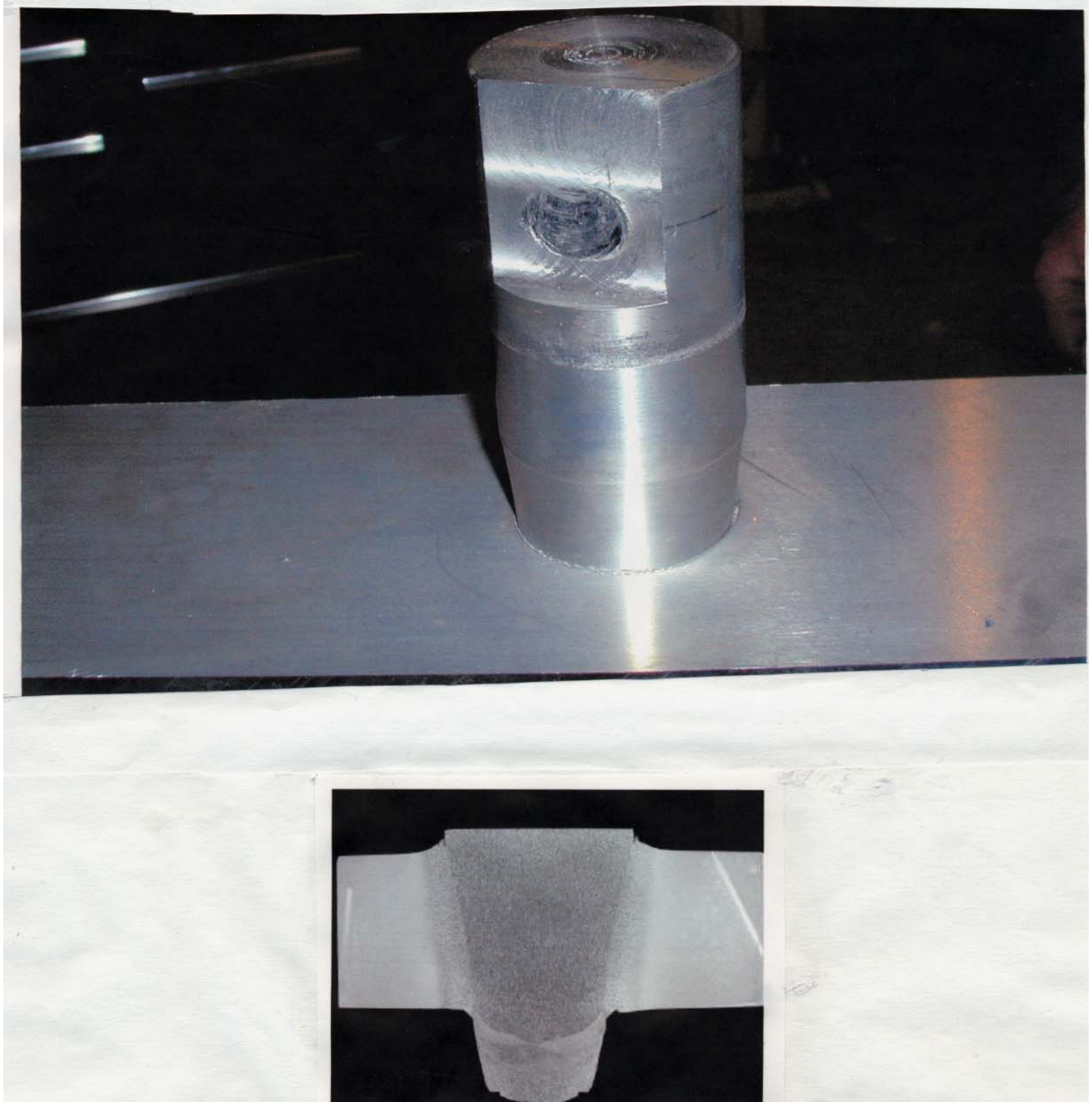
1. The challenge in FSW of circumferential parts is providing a backing support for the part. For single-sided FSW the forces are in the range of 6000 kg. for this alloy and thickness. The force has to be reacted from the back of the weld, making assembly and disassembly difficult. To back up the weld from inside the vessel, several options were considered. The approach chosen was the bobbin tool or self-reacting tool (SRT). The SRT uses a second FSW shoulder on the backside of the weld to react the loads. This eliminates the need for internal tooling. The SRT uses a scrolled shoulder for normal-to-the-surface welding allowing for the second shoulder to be used on the back-side of the weld. The SRT was selected for welding of the firing vessel. AJT's conventional FSW machine has a rotary device for circumferential welding. This device was used with the SRT machine to weld the vessels.

Initial welding development was done on 2.54 cm. thick 2219-O and 2219-T651 material. When the 3.8 cm. thick- material became available, efforts were shifted to the thicker material. The torque demand became greater and some modification of the friction-stir welder was necessary.

AJT performed circumferential weld demonstrations on 2.5 cm. thick rolled plate. The plate was rolled to 102 cm. OD and was 122 cm. in arc length. The demonstration was used to test the modified rotary drive mechanism. It was necessary to install a planetary gear reducer in line to achieve more rotary power. Upon completion of the gear reducer installation a successful circumferential demonstration was performed.

2. Closing out the circumferential friction-stir weld--Once friction-stir welding is complete, a keyhole is present due to tool retraction. Trimming off the keyhole is not an option in circumferential friction-stir welding. A closure method needed to be identified. Examples of closure methods are: a run off wedge, retractable pin tool (RPT), friction-plug welding, and fusion fill. The most viable keyhole closure method for self-reacting friction-stir welding is friction-plug welding, which maintains the solid-state structure of the friction-stir weld.

An inertia welder was used to develop process-parameters for the friction-plug welded close-out. AJT designed a plug and hole configuration that allowed the entire welding cycle to be completed in a single operation. Initial friction-plug welding trials resulted in the 2219 Al alloy plug shearing halfway through the thickness of the friction-stir weld. The plug was 2219-O to match that of the friction stir welded vessel. The shearing of the plug caused the bottom half of the plug to stop rotating, creating a poorly bonded interface. AJT decided that a 2219-T6 plug was the next option to be evaluated. Weld trials showed promise, but the upper portion of the weld was not bonded due to the harder condition of the plug. The welding parameters were adjusted to allow for some softening of the plug at the topside. This resulted in sound plug-welds being made into flat plate (figure 3).



2219-T 6 Aluminum Alloy Plug Friction-Plug Welded into a 1.5" Thick Bobbin-Tool Welded 2219-O Aluminum Alloy Plate

FIGURE THREE

MECHANICAL PROPERTIES OF THE FRICTION-STIR WELDS

1. Tensile properties-The room-temperature tensile properties of friction-stir welded 2219 Al alloy plate with various combinations of welding-parameters and heat-treatments are summarized in figures 4-5.

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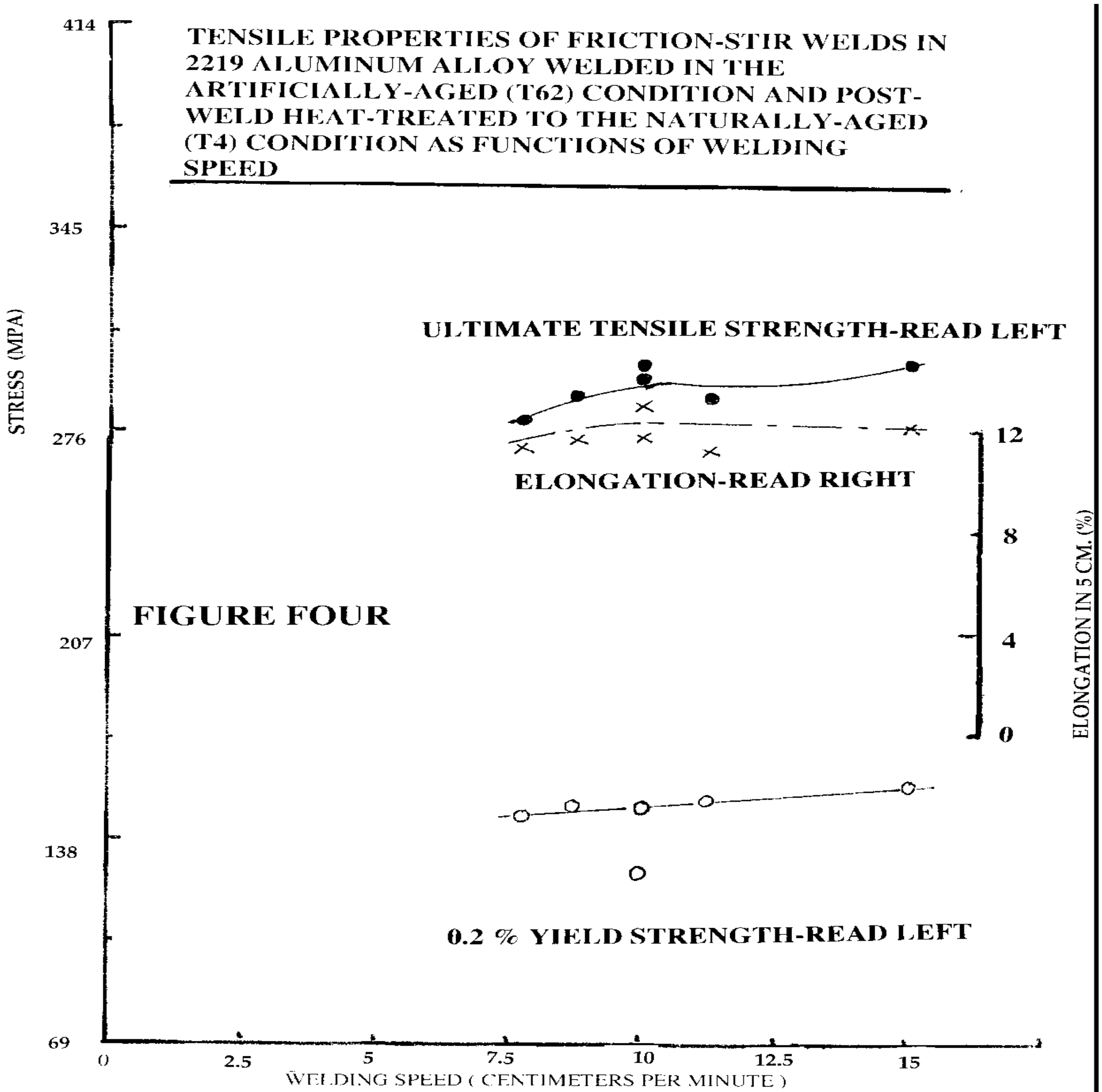
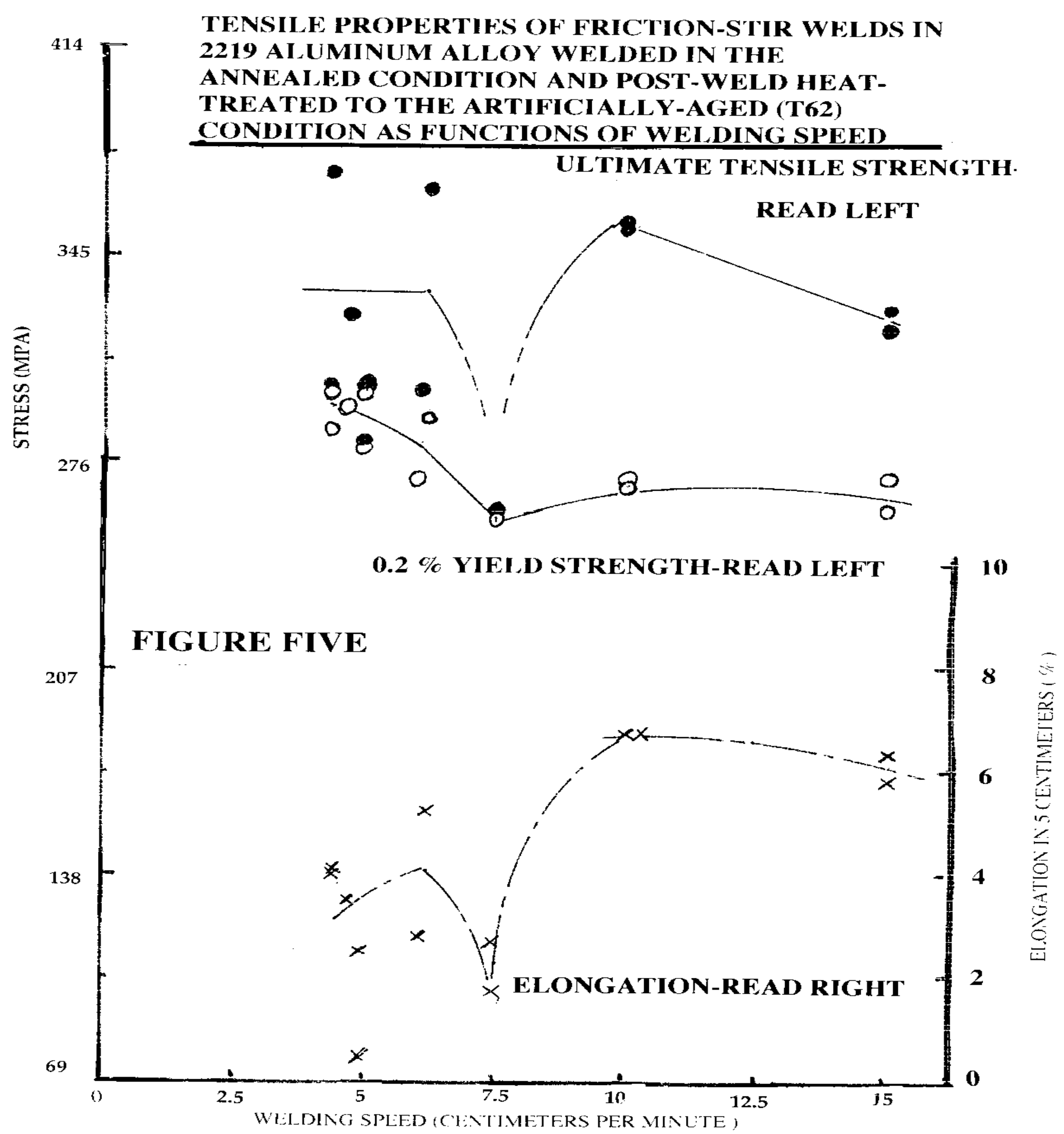


Room-temperature tensile and elastic-plastic fracture-toughness properties of friction-stir welds that were solution-treated, quenched, and artificially aged to the "-T62" condition after welding were determined. Tensile samples, with a 0.635 cm diameter and 2.54 cm. gage-length, were removed from the top, center, and bottom thirds of the welds, with the samples oriented in the longitudinal (along the weld-axis) and long-transverse (normal to the weld axis) directions. Tensile tests were conducted per ref. 5.



Tensile properties of friction-stir welds made in fully-aged (-T62) 2219 Al alloy, followed by testing in the "as-welded" (actually after natural-aging for 2-3 weeks), are presented as a function of welding speed in figure. 4. The ductility, expressed in terms of the total-elongation in a 5 cm. gage-length, is between 10.5 % and 13 %, and does not vary systematically with increasing welding-speed. The 0.2% offset yield-strength values ranged from about 145 MPA to 155 MPA as the welding-speed was increased from 7.5 cm. per minute to 15 cm. per minute. Ultimate tensile strength values increased from about 280 MPA to 305 MPA as the welding-speed increased from 7.5 cm. per minute to 15 cm. per minute.

Using the base-metal minimum yield-strength of 276 MPA results in joint-efficiency values based on the ratio of "as-welded" yield-strength to minimum forging yield-strength of 52% to 56%. In a similar manner, i.e., using the minimum base-metal ultimate tensile strength of 400 MPA, the joint-efficiency based on ultimate tensile strength ranged from 70 % to 76 %. These joint-efficiency values were inadequate for the intended application.

The low joint-efficiencies of welds in the naturally-aged (-T4) condition led to extensive weld-parameter exploration followed by a complete solution-treatment (995 +/-10 F), a water-quench, and artificial aging heat-treatment of 375 +/- 10 F for 36 hours, which is the heat-treatment cycle recommended for the base-material (ref 4). Tensile properties of friction-stir welds made in the annealed (-O) condition, followed by the previously-described heat-treatment, which rendered the weld in the fully-aged (-T62) condition, are presented in figure 5 as functions of welding-speed. The ductility, expressed in terms of the total elongation in a 5 cm. gage-length, varied between 0.5 % at lower welding-speeds (5 cm. per minute to 7.5 cm. per minute) to as high as 6.6 % at a maximum welding-speed of 15 cm. per minute. The 0.2 % offset yield-strength values ranged from about 293 MPA to about 267 MPA as the welding-speed increased from 4 cm. per minute to 15 cm. per minute. Ultimate tensile strength values varied widely at lower welding-speeds (from 4 cm. per minute to 6 cm. per minute), with values ranging from 280 MPA to about 371 MPA. At a welding-speed of 7.5 cm. per minute, the ultimate tensile strength went through a minimum of about 259 MPA. At higher welding speeds (10 to 15 cm. per minute), the ultimate tensile strength values decreased with increasing welding-speed from about 354 MPA to about 323 MPA. As before, using the base-metal minimum yield-strength value of 276 MPA, the joint-efficiencies for the post-weld heat-treated friction-stir welds ranged from 97 % to 106 %. In a similar manner, i.e., using the base-metal minimum ultimate tensile strength value of 400 MPA, the corresponding joint-efficiencies ranged from about 93 % at a welding-speed of 4 cm. per minute to about 80.8 % at a welding-speed of 15 cm. per minute.

After review of the weld-process development and tensile test results, LLNL and AJT selected a set of weld-process parameters which yielded the following mean tensile properties when using a welding-speed of 5.75 cm. per minute: ultimate tensile strength-370 MPA; 0.2 % offset yield-strength-293 MPA; and total elongation-5.2%. These strength-values corresponded to a joint-efficiency of 92.5 % based on minimum ultimate tensile strength of the base-metal, and a joint-efficiency of 106% based on the minimum yield-strength of the base-metal.

2. Ductile fracture-toughness- Compact-tension samples (0.5 T; ref. 6) were removed from the top, center, and bottom thirds of welds made with the optimized process-parameters. The notch and pre-crack were located along the weld-axis and running from the face to the root of the weld (so-called “TL ”orientation) per ref 7, or with the notch and pre-crack located normal to the weld-axis and running from the face towards the root of the weld (so-called “LT” orientation per ref. 7). Also tested were several 0.5T fracture-toughness samples removed from drop-offs from one of the forgings. All fracture-toughness samples were heat-treated to the fully-aged (-T62) condition before machining of the notch and pre-cracking.

Testing was done at room temperature per ref 6, and the data analyzed to determine both ductile fracture-toughness (Jic) and linear-elastic (Kic) values per ref 6. All samples yielded valid Jic values that ranged from 21.36 KJ/M^M to 37.73 KJ/M^M. Kjc results, converted from the Jic values by the method described in ref. 8, for the forgings and friction-stir welds, are compared with published values from friction-stir welded Al alloys (ref.9) in figure 6, in the form of a plot of Kjc vs. 0.2% offset yield-strength. Note that the individual values for the heat-treated friction-stir welded 2219 Al alloy mostly are above the least-squares trend-line for the other Al alloys, indicating the good fracture-resistance of the heat-treated 2219 friction-stir welds. No consistent difference was seen in the Kjc results for friction-stir welds with the crack oriented in the TL versus LT orientation. The fracture-toughness values of the heat-treated 2219 forging-samples fell somewhat below the least-squares trend-line for the other alloys.

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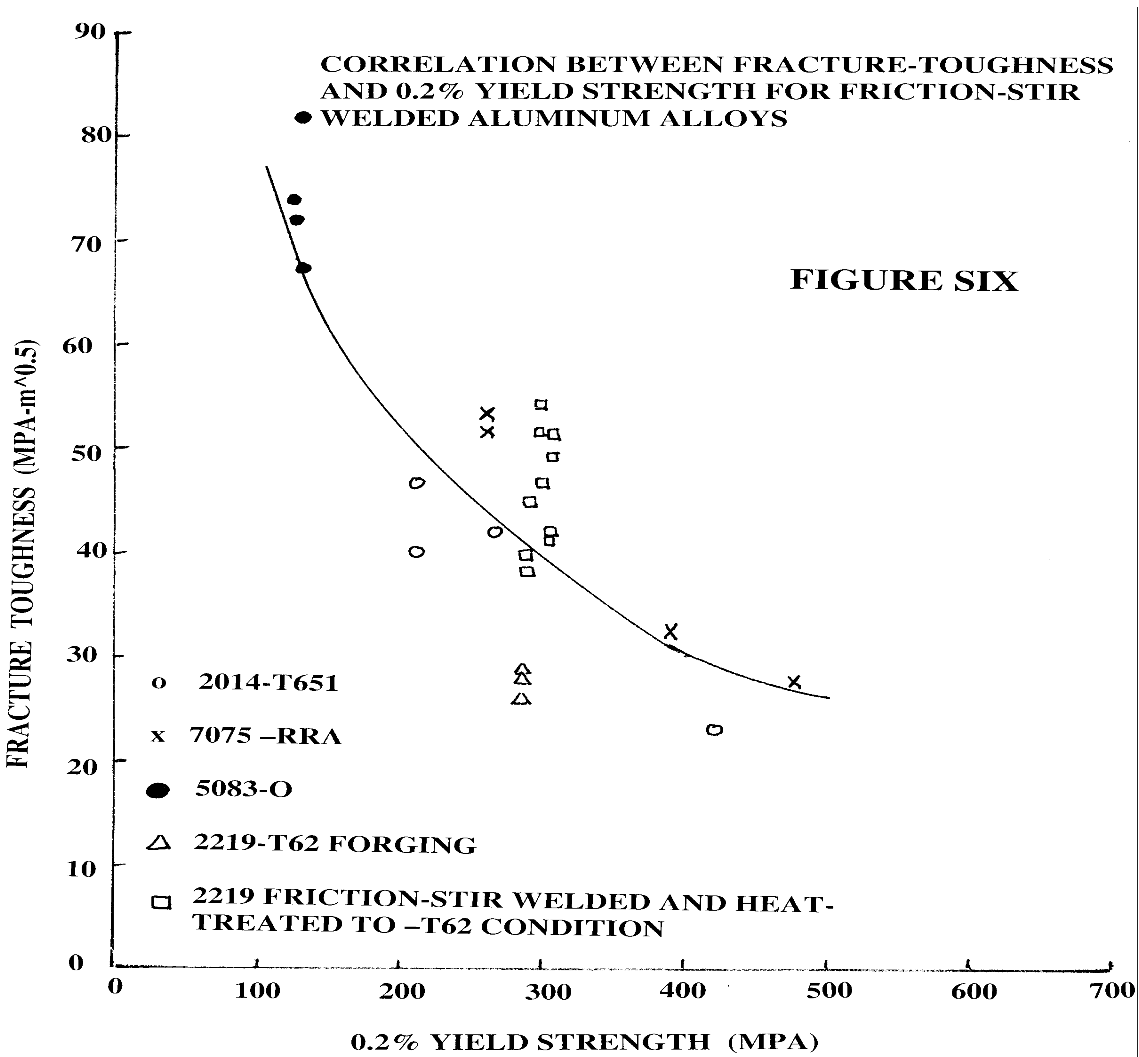
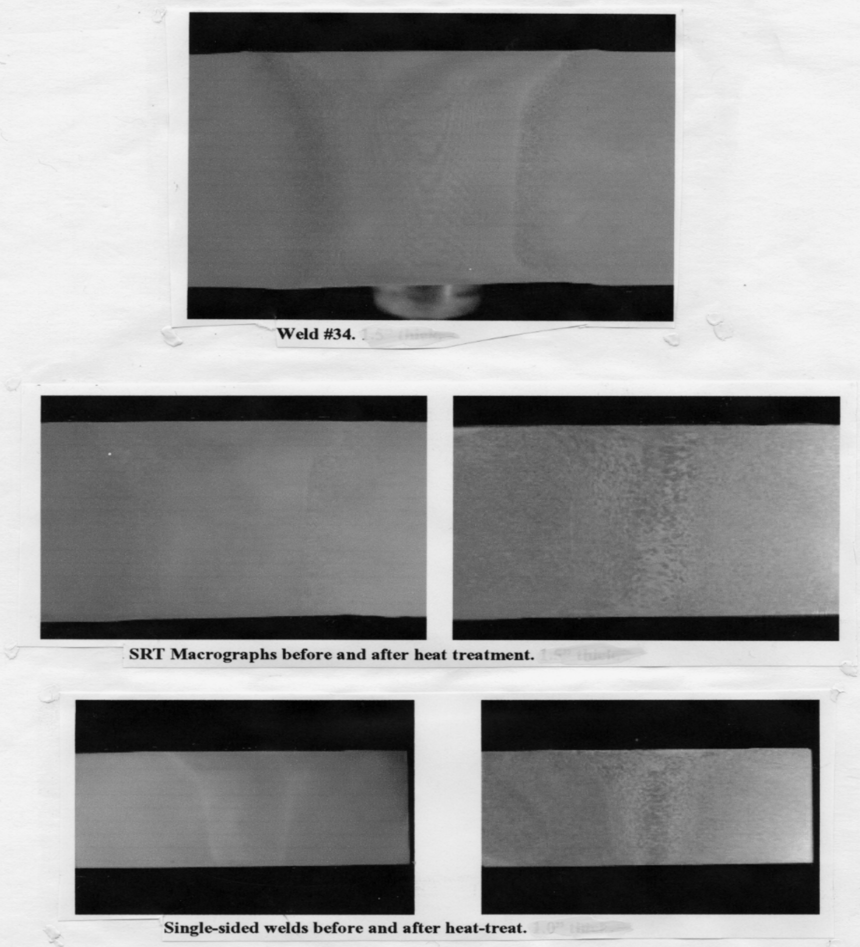


MACROSTRUCTURE AND MICROSTRUCTURE OF FRICTION-STIR WELDED 2219 ALUMNUM ALLOY

Plates welded in the annealed condition had abnormal grain growth in the FSW nugget due to weld-induced solution heat treatment (figure 7).

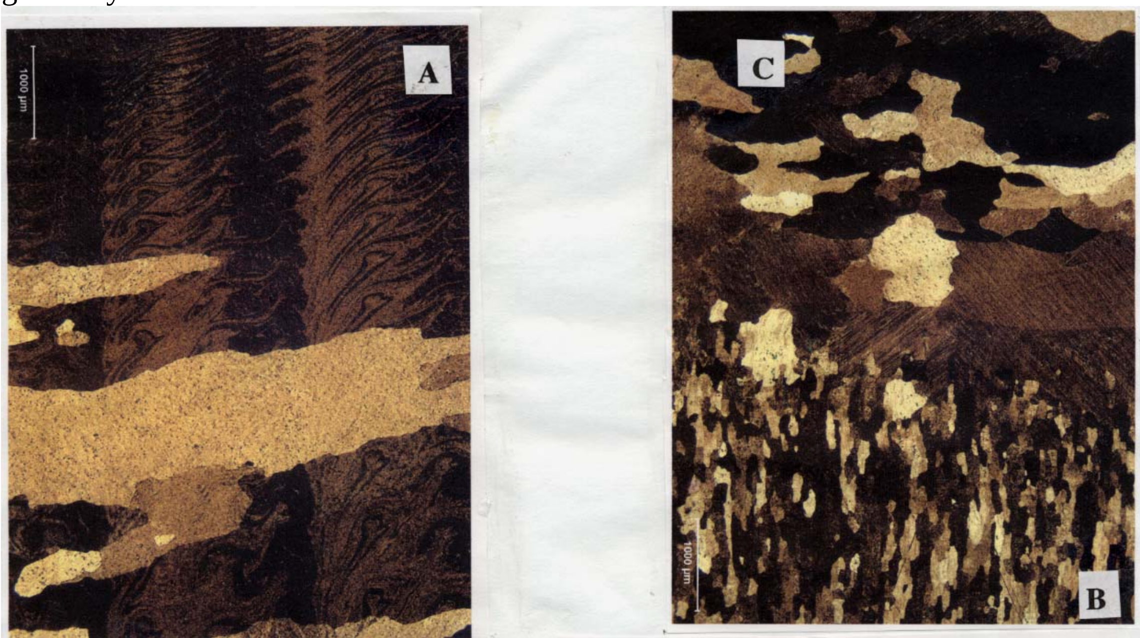


MACROSTRUCTURES OF VARIOUS FRICTION-STIR WELDS IN 2219 ALUMINUM ALLOY PLATE

FIGURE SEVEN

The large grain growth in the nugget resulted in decreased ductility and transgranular fracture. The large grains in the nugget cause a slight decrease in ultimate tensile strength. Plates welded in the -T62 condition had much greater elongation than those described above. However, the welding-induced heating caused significant decreases in both yield strength and ultimate tensile strength due to precipitate coarsening in the heat-affected and thermo-mechanically affected zones. Tensile specimens displayed microvoid-coalescence fractures in the heat-affected zone, with less than 75% joint efficiencies based on tensile yield strength.

Microstructures of heat-treated welds are shown in figure 8. Note the swirled structure in the weld-region (figure 8, feature ”A”), as well as the large grains growing across the weld-region. Contrast the coarse-grained weld-region (figure 8, features ”A” and “C”) with the fine-grained thermo-mechanically-affected zone (figure 8, feature “B”). The same grain growth phenomenon occurred in the Self-Reacting Tool (SRT) welds and in the single-sided welds. Initial SRT weld-tensile specimens failed by the same trans-granular mechanism. Later SRT weld-tensile specimens displayed increasing amounts of a microvoid-coalescence failure mode due to improved welding parameters and tool geometry.



NOTE SWIRLED STRUCTURE (A) IN CENTER OF WELD (LEFT)

NOTE FINE-GRAINED THERMOMECHANICALLY-AFFECTED ZONE (B) AND COARSE-GRAINED WELD (C) (RIGHT)

FIGURE EIGHT

MICROSTRUCTURES OF FRICTION-STIR WELDS IN 2219 ALUMINUM ALLOY PLATE.

Once a set of weld-parameters was found that yielded acceptable tensile-test results to both LLNL and AJT, two welded panels were made with these SRT weld-parameters. One of these welds was cut into two pieces, and these pieces were used as control samples for vessel heat treatment. Tensile and ductile fracture-toughness samples were removed from these heat-treatment witness plates, and tested as described above. The results are presented in figures 5 and 6.

WELDING OF THE VESSELS

1. Tack Welding- AJT tack welded the vessel halves together using a single-sided friction-stir welding tool. The tool created a tack weld that was 1.02 cm. deep. Once tack welding was completed, the clamping mechanism was disassembled. The tack weld supported the full weight of the free half-vessel.

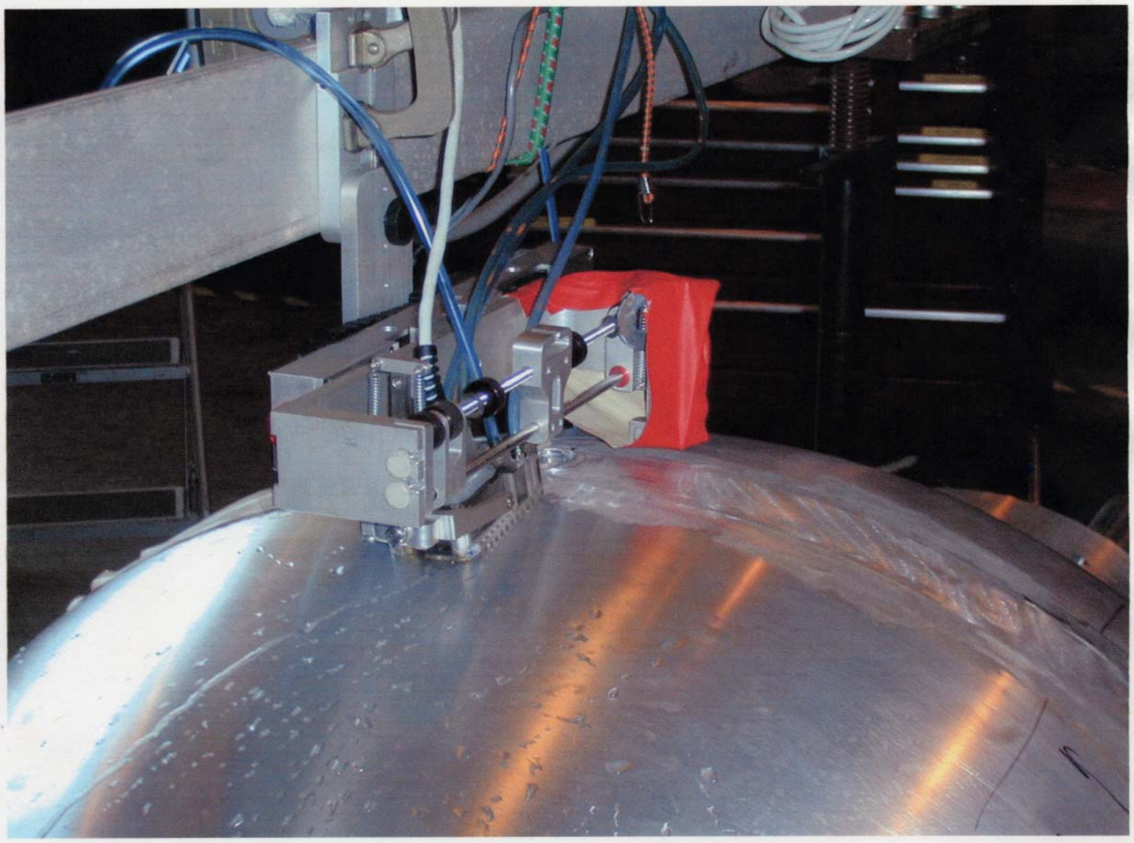
2. Vessel self-reacting tool friction-stir welding--Vessel B was the first to be welded.

With the clamping mechanism disassembled, a through-hole was drilled at a slight angle toward the retreating side of the weld. This was done to compensate for deflection seen in the tack welding and in the circumferential demonstration plates. Since the joint was within the pin diameter path and was favoring the retreating side of the weld, the alignment was acceptable. The self-reacting tool was assembled on the outside of the part. The pin was fed through the drilled hole and the lower shoulder was attached. The entire clamping mechanism was reassembled and the circumferential weld was made.

Vessel A was prepared in the same manner as vessel B. The hole was drilled favoring the retreating side of the weld. Again the machine saw minimal deflection. Both inside and outside weld surfaces were satisfactory.

3. Vessel friction-plug welding--Both vessels were welded using the friction-plug welding process developed on flat plate. Friction-plug weld tooling and the inertial welder performed as expected. Ultrasonic inspection of the friction-plug welds revealed minor indications, most of which were within 0.64 cm. of the face-surfaces of the welds. These indications were removed by subsequent finish-machining of both vessels.

4. Non-destructive examination of the friction-stir welds and the friction-plug welds was performed using a combination of straight-beam ultrasonic examination and phased-array ultrasonic examination (figure. 9, ref. 10).



PHASED-ARRAY ULTRASONIC EXAMINATION OF A FRICTION-STIR WELD

FIGURE NINE

Ultrasonic inspection performed on the circumferential weld on vessel B revealed a small continuous channel defect located in the bottom half of the weld. It is likely that the defect was due to the compound curvature of the spherical vessel. The circumferential weld had been made using process-parameters that were based on results obtained with the same weld-parameters used in flat plate and cylindrical plate welding. Repairs were accomplished by re-welding the vessel with increased pressure and increased travel speed to eliminate the channel defect. The vessel was re-welded using the procedure described above. Ultrasonic inspection revealed only minor indications (less than 0.14 sq. cm. by 0.635 cm. long) in the start and overlap areas of this weld. Phased-array ultrasonic examination of the circumferential weld in vessel A revealed no indications.

PRELIMINARY FRACTURE ANALYSIS

Some preliminary static fracture-mechanics analyses have been performed. It was assumed that an undetected semi-elliptical flaw, 0.25 cm. deep by 0.635 cm.,long.was located close to the external or tension-surface of the vessel. Tensile stresses close to the yield-strength of the weld, or about 276 MPA, were obtained from stress-analyses performed during design of the vessel. The minimum linear-elastic fracture-toughness, converted in the usual manner (ref. 9) from the elastic-plastic fracture-toughness values for 2219 friction-stir welds (fig. 6) was used. The results indicate that at stresses of 276 MPA, the calculated stress-intensity for the assumed flaw is about half that expected for an aluminum alloy with a yield-strength of 276 MPA. Additional fracture-mechanics analyses, for both static and fatigue loading, will be carried out once the results of fatigue-crack growth testing of the 2219 friction-stir welds is completed.

CONCLUSIONS

1. Bobbin tool friction-stir welding produced satisfactory joints in 3.8 cm. thick 2219 aluminum alloy.
2. Friction-plug welding produced satisfactory close-out welds in the circumferential welds.
3. Post-weld solution-treatment, quenching, and artificial aging was necessary to restore the welds to near base-metal strength, ductility, and toughness.
4. A combination of straight-beam and phased-array ultrasonic examination found a few defects of sizes of about 0.14 sq. cm. by 0.64 cm in length in the welds.
5. Satisfactory repair welds were made by friction-stir welding over the defective region in the original weld.
6. Preliminary fracture-mechanics analyses indicate that the welds are fit for the intended service.

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