

Advances in Friction Stir Welding for aerospace applications

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Friction stir welding (FSW), an innovative solid-state joining technique, is finding greater use in aerospace applications through advances in materials development evaluations, structural design and testing programmes, tooling and process innovations, and standards and specification developments.

To advance FSW from the research stage into direct application, performance and properties data are needed. Therefore, the NIAR in Wichita, Kansas, began a multi-pronged approach to facilitate technology transfer of friction stir welding into production applications. Research programmes are focused on materials evaluations (e.g. corrosion resistance), structures evaluations, weld tool development, and process innovations.

This article is an edited version of the expert paper and summarises the findings that were underpinned by detailed tests whose results were provided and are logged at WSU. A major conclusion is that significant advances continue to be made.

Introduction

Patented in 1991 by The Welding Institute, Ltd. (TWI), friction stir welding (FSW) is an environmentally friendly, lean manufacturing process with potential for revolutionising the aerospace industry. Eclipse Aviation, for example, has reported dramatic production cost reductions with FSW when compared to other joining technologies.

With the need to continually find methods for reducing manufacturing time, increase reliability, and decrease costs, FSW is one technology that aerospace manufacturers cannot afford to ignore. FSW is a solid state welding process capable of joining almost any type of metal, including some previously unweldable precipitation strengthened



Brian Tweedy

2000 and 7000 series aluminium alloys.

FSW may be characterised as a forging and extruding metalworking process.

In the initial stage of the process, a cylindrical tool composed of a probe and shoulder, is rotated and slowly plunged into the joint line of the materials to be joined. The non consumable weld tool generates heat through friction and plastic strain energy release during mechanical deformation of the work piece, thus softening the material. Then, as the tool is traversed along the joint line, material is extruded around the weld tool probe while simultaneously being forged into a consolidated joint by the pressure exerted through the weld tool shoulder.

Joints produced in this way have higher strengths than riveted joints and much lower residual stresses than typical fusion welded joints.

With funding primarily from the State of Kansas and the Federal Aviation Administration, the Advanced Joining Lab in the National Institute for Aviation Research (NIAR) of Wichita State University (WSU) is conducting research and development programmes that

extend from basic research to prototype development. Specifically, these programmes include research on materials evaluations (e.g. corrosion resistance), structures testing, weld tool development, and analysis of process innovations.

A friction stir weld is typically characterised as being comprised of three primary zones: the heat-affected zone (HAZ), the thermomechanically affected zone (TMAZ), and the dynamically recrystallised zone (DXZ) or weld nugget.

Tensile failure in transverse tensile tests most often occurs within the HAZ or the section between the HAZ and the TMAZ. In this region, elevated temperatures generated during the FSW process dissolve Guinier-Preston (GP) zones and coarsen strengthening precipitates, creating a local strength minima in the region.

Due to the change in precipitate morphology, this region is also generally susceptible to corrosion. One way to potentially improve the resulting corrosion properties is through post-weld artificial ageing (PWAA) treatments. Therefore, a study was initiated to develop an understanding of the effect that thermal transients produced during FSW have on precipitation-strengthened alloys.

Post-weld artificial ageing of 7075 and 2024

A goal of this research was to identify proper initial temper selection and post-weld ageing treatments for the enhancement of the corrosion resistance of both 2024 and 7075 alloys and their dissimilar joints. Initially, the alloys tested included 7075 in the -T6 and -T73 tempers and 2024 in the -T3 and -T81 tempers.

Butt welds were made in 0.125 inch thick plates with a weld tool, having a fixed probe and a concave shoulder, at 600 rpm and 8 ipm under load control. Samples were machined from steady-state

portions of the weld and were evaluated using optical microscopy, microhardness, electrical conductivity, tensile, and exfoliation corrosion testing. Heat treatments were selected based on conventional precipitation heat treatments for each alloy and from the literature.

Overaged tempers, such as -T81 and -T73, are considerably more stable in terms of precipitate morphology, i.e. they are less susceptible to microstructural change during welding than are the peak hardness tempers, e.g. -T3 and -T6 tempers.

Therefore, it is expected that a greater response to FSW will be observed in 2024-T3 and 7075-T6 than in 2024-T81 or 7075-T73, respectively. To test the material responses, coupons were prepared for exfoliation testing per ASTM G-34 from welded coupons.

A range of heat treatments were applied prior to testing. Exfoliation samples were then exposed for 96 hours.

All naturally aged specimens showed obvious signs of severe attack in the weld region, except 2024-T81, which had excellent exfoliation resistance in the as-welded condition. None of the treatments were successful in restoring the beginning exfoliation corrosion resistance to 7075-T6, including the RRA treatments, which exhibited pitting in the HAZ in all cases.

Beneficial treatments were found, however, for both 2024-T3 and 7075-T73. A beneficial treatment was also demonstrated for a 2024-T81/7075-T73 dissimilar joint. Previous attempts to create a 2024 to 7075 dissimilar joint resulted in extreme corrosion attack in the weld zone.

Pitting occurred in the naturally aged coupon. However, pitting was suppressed in the sample aged 4 hours at 325°F. Neither weld had significant corrosion attack in the DXZ where the two alloys have been interspersed.

Electrical conductivity and microhardness testing were performed to validate and explain the beneficial changes in the corrosion behaviour of selected welds.

Test results confirm that marked improvements can be made in the electrical conductivity for 7075-T6 and 7075-T73 through post-weld ageing. For both 7075-T6 and 7075-T73, increased electrical conductivity is achieved with PWAA. It was noted that 7075-T6 maintains an "M" profile even with PWAA, whereas 7075-T73 has a more uniform



Christian Widener

response across the weld zone. This result is possibly related to the pitting response observed in 7075-T6, which was absent from 7075-T73 samples with PWAA. There was also an improvement in electrical conductivity response for 7075-T73 with natural ageing prior to PWAA.

The conclusions of the initial materials study are:

- 1) artificial ageing to a full or partial overage -T81 temper is required to improve the exfoliation resistance in the weld zone of welded 2024 in the -T3 temper;
- 2) 2024 aluminium should be welded in the overaged -T81 condition to the maximum corrosion resistance condition when no PWAA is applied;
- 3) welding 7075-T73 followed by PWAA is preferable to welding this alloy in the -T6 temper followed by ageing to -T73 because of higher tensile and yield strengths and better exfoliation corrosion resistance;
- 4) retrogression and reaging treatments do not appear to improve joint properties of -T6 aluminium due to the severity of the overaging in the HAZ caused by FSW; and,

- 5) the PWAA treatment of 4 hours at 325°F provides benefit by stabilising the microstructure and enhancing corrosion resistance while not invalidating the bulk material properties of 7075-T73 per AMS 2770 rev G.11 Finally, a dissimilar joint with good corrosion resistance is possible between 2024-T81 and 7075-T73 when the 2024-T81 is on the advancing side, followed by PWAA for either 100 hours at 225°F or 2-4 hours at 325°F.

Post-Weld artificial ageing of 7136 and 7249

The United States Navy has approved several high strength aluminium alloys, including 7249-T76 and 7055-T74, as replacement alloys for 7075-T6. In addition, Universal Alloy Corporation (UAC) has recently developed another high strength alloy, 7136, for aerospace applications.

To extend the initial work on 7075, both 7136 and 7249 extrusions 0.250 inch thick were welded and tested in a similar manner discussed in the previous section.

The alloys were received in the intermediate -W condition and then artificially aged to a stable intermediate condition. Without a final artificial age the material would continue to naturally age indefinitely.

A strong correlation exists between the electrical conductivity and the resistance to stress corrosion cracking (SCC) on the as-welded and artificially aged FSW joints in 7xxx alloys. Therefore, several processing sequences were tested. Samples tested in the as-welded condition were stabilised with heat treatment of 250°F for 24 hours. PWAA both stabilised the FSW samples and improved or restored their resistance to corrosion. Electrical conductivity and microhardness were then used to characterise the effect of the heat treatments on the joints and parent material.

Higher strength

In summary, when joining the higher strength 7000 series aluminium alloys, post-weld ageing is necessary to stabilise the microstructure in the friction stir welded regions. Overaging treatments can improve the corrosion resistance of the alloys. The ageing from a peak temper (-T6) to an overaged -T7x temper as well as an additional overaging treatment of the FSW specimens welded in the -T7x temper will raise the electrical conductivity.

This is expected to result in an improvement or restoration of the SCC resistance of the FSW weldments and restore or improve exfoliation corrosion resistance. Research is ongoing in the Advanced Joining Laboratory at the NIAR at WSU to further evaluate the results of the FSW process on 7136 in order to increase the joint efficiency and

better understand the response to PWAA treatments.

Structures evaluations

The United States Air Force Academy has studied the response of flat stiffened panels under static compression and shear loading with and without dents. The panels were based on the configuration of an existing airframe structure. The Advanced Joining Lab of NIAR began investigating the response of similar panels fabricated using FSW panels (without dents) to evaluate how FSW performs as a replacement joining technology in airframe applications.

Performance and properties data for friction stir welded structures are required if this innovative joining technology is to replace riveting, the conventional joining technology for building airframes.

To begin developing the required data, flat stiffened panels were fabricated with two hat-section stiffeners using FSW. The stiffened panels were then tested statically in tension, compression and shear and the results were then compared to finite element models to evaluate the ability of the models to predict the load-carrying capability of a unitised FSW structure.

The results were also compared directly to riveted panels with identical geometry in order to evaluate the static strength performance of the FSW panels.

Processing parameters

Prior to the fabrication of stiffened panels, friction stir welded lap joint coupons were produced and tested with dissimilar aluminium alloys (2024-T3 and 7075-T6) to simulate a joint between a stiffener (7075-T6) and a skin (2024-T3). A satisfactory set of processing parameters based on low magnification optical microscopy was developed for the dissimilar alloy lap joints. A simple tapered conical pin with three flats was used to produce the welds. Advancing and retreating side locations on the joint configuration were alternated to determine optimal design arrangement.

Lap joint strength was determined using unguided lap shear in friction stir welded joints. In addition, the load carrying capability, in terms of pounds per inch of weld, was documented.

The location of the advancing and retreating side with respect to the load path is designated as A-loaded and R-loaded, respectively. A-loaded is the



Dwight Burford

designation given when the advancing side is in the load path and, similarly, the R-loaded is when the retreating side is in the load path.

Tension, compression, and shear tests were conducted on a 110-kip load frame. In the tension tests, the stiffeners were attached completely across the panel, and the test configuration applied tension perpendicular to the joint. In both the tension and shear tests, doublers were attached at the ends of the panel in order to develop sufficient bearing strength for testing the panels to failure.

The tension fixture was installed into the MTS load frame with the normal clevis and pin hardware with instrumented strain gauges.

For the compression testing, a resin support was used at the ends to introduce a smooth and equal load transfer into the panels.

In both the tension and compression tests, the strain gauges were also used to ensure symmetric loading of the panels. For each testing mode, three panels were used.

Tension

In tension, the FSW panels showed a 10 per cent increase in UTS and a 41 per cent increase in total elongation over the riveted panels. The failure mode for both the FSW and the riveted panels was stiffener separation at the joint line. The riveted panels yielded earlier than did the FSW panels and catastrophically failed at a lower stress level than did the FSW panels.

Compression

Strain gauges and photogrammetry were used to measure the strains present in the compression panel testing. The riveted panels carried a maximum load of 20,752lbs while the FSW panels carried a maximum load of 20,862 lbs. Buckling of the skin of the panels initiated prior to failure and required the stiffeners to carry the majority of the load. In compression, the effective skin width was calculated to be only 0.72 in. and subsequently determined the width of the panels.

It also showed that the majority of the skin was not effective in carrying a compressive load. The strain in the skin was greatest between two stiffeners and the average strains on back to back gauges were approximately zero. These two results confirmed the inability of the skin to pick up any load in compression.

This was also shown by Guijt et al in a study investigating the effect of dents in similar panels.

Because the stiffener is the primary load carrying component of the panel, the ultimate load for both the FSW and the riveted panels appears to be approximately equivalent. The peak stress for the FSW and riveted panels is 21.7 and 21.4 ksi respectively, the difference between which would be within experimental error.

However, the FSW panel had a greater crosshead deflection than the riveted panel. For both panels, stiffener buckling appeared to be the failure mode. The FSW panels appeared to continue to buckle after failure while the riveted panel failed catastrophically. In a prior study by Arbegast et al., it was found that friction stir welded panels failed at lower panel loads than an equivalent riveted panel in compression testing.

Shear

There were significant results in load displacements for the FSW shear panels. Tests demonstrated that the riveted panel exhibited failure at an ultimate load of approximately 32,300 lbs, whereas the FSW panels carried 35,100lbs on average.

This correlated to an eight per cent higher panel load carrying capability. During testing, the FSW panels failed very distinctively. First, one of the stiffeners separated partly from the skin, but the structure retained its residual strength

and continued to carry load. Then the panels failed by a crack running from the weld to the shear frame. Initial stiffener failure occurred at 33,000lbs for two of the panels and 31,500lbs for the other.

The FSW panels were shown to be able to dissipate strain energy less abruptly than the riveted panels by continuing to carry a load while sustaining stiffener damage. The riveted panels, on the other hand, reached an ultimate load and failed catastrophically when a tear ripped across both stiffeners. The tear appeared to have jumped across stiffeners in the riveted panels, while a similar tear in the FSW panel appeared to turn back to the frame when it reached the joint. The energy absorbed by each panel is represented by the area under the load-displacement curve for each panel.

Friction Stir Spot Welding

Friction stir spot welding (FSSW) and discontinuous friction stir welding (DFSW) have the unique characteristic of being lap welds with parent material spaced between the joint locations. Further, in swept spot welds, the relative direction of travel and tool rotation will place either the advancing or retreating side of the weld to the outside and, thus, affect the mechanical properties of the joint.

Testing has been conducted to evaluate the static strength of panels built with swept spot welds, and work is planned to evaluate the fatigue performance of these panels. From a structural analysis perspective, it is expected that FSSW and DFSW structure can be evaluated in much the same manner as riveted panels or resistance spot welded panels. Unlike riveting (but similar to resistance spot welding), however, the material in a joint location of FSSW and DFSW joints is effectively thicker than either component. Therefore, crack behaviour around a FSSW or DFSW joint location should be significantly altered from that in a riveted joint location.

An investigation of spot weld strength in dissimilar 2024-T3 to 7075-T6 stiffened panels was conducted in preparation of the structural testing of FSSW panels joined with swept spot welds. A tool with a relatively small probe and shoulder (relative to sheet thickness) was used to sweep out a track.

Testing was completed to determine the optimum swept spot diameter and lead

angle to the spot rotation to increase weld strength. High strength swept spot weld strengths were achieved in bare similar 2024-T3 material. In a panel where both the stiffeners and skin were 0.04 inches thick, spot strengths in excess of 1,200lbs per spot were achieved.

By decreasing the probe and shoulder diameters and increasing the size of the stirred zone for the spot weld, a much larger shear area through the thickness of the sheet was achieved, resulting in higher test strengths. The addition of the lead angle also helped maintain forging pressure, thereby increasing spot strength.

Once the optimization development testing was complete, a shear panel was constructed and tested in shear. The panel achieved a similar displacement and load to the FSW lap weld panels, all of which exceeded the performance of the riveted panels.

Regarding energy release upon failure, the FSSW panel also failed in a less abrupt manner and with less audible noise at failure compared to the riveted panels.

The next step

The next step of this investigation will be to evaluate the fatigue behaviour of swept friction stir spot welded and discontinuous friction stir welded panels.

Factors which are expected to influence the outcome of the test programme include the presence of the double-thick effect of a FSSW or DFSW countered by the presence of a HAZ around each spot. Weld size, weld pitch, and the corresponding parent material spacing will also factor into the design and results.

Weld tool development

In an effort to reduce surface damage in butt joints, lap joints, and friction stir processed material, weld tools with different scroll patterns were tested to improve weld track properties.

Measurable smoothing of the surface finish was achieved by incorporating a unique feature, termed the Wiper (patent pending), on the shoulder face.

In addition to reducing surface roughness, the Wiper feature appears to result in a reduction of shearing deformation damage in the microstructure adjacent to the weld track surface and, thus, provides better fatigue-resistant properties in the as-welded weld track.

Shoulder configuration development

The shoulder of FSW weld tools directly and indirectly influences many properties within a weld.

Among its key functions is the containment and consolidation of material in the weld zone. In developing shoulders for improved weld track properties, consideration was given to the influence the shoulder has on surface damage and internal material flow.

Surface damage in the weld track is influenced by the rotational flow generated by the tool and the force distribution under the shoulder, which in turn is controlled by the geometry of the shoulder and how the tool is orientated relative to the work piece surface.

The shoulder contribution to material flow depends upon how well it functions to direct work piece material toward the probe. A shoulder with a sufficient inwardly-directed traction force is needed to contain the work piece material.

Overly aggressive shoulder features can leave damaged, i.e. non-uniformly strained, torn and roughened, surface material.

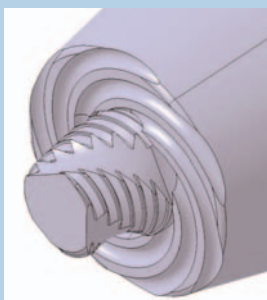
Scrolls are among the most useful geometric features used for developing an inwardly-directed traction force under FSW tool shoulders and may be used either in a single or multiple scroll configurations.

I Nomenclature

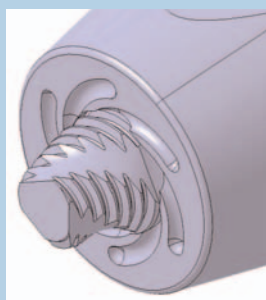
DFSW	=	discontinuous friction stir welding;
DXZ	=	dynamically recrystallised zone;
FSSW	=	friction stir spot welding;
FSW	=	friction stir welding;
HAZ	=	heat affected zone;
HRS-FSW	=	high rotational speed friction stir welding;
ISZ	=	Induced stir zone
PWAA	=	post-weld artificial ageing;
TMAZ	=	thermo-mechanically affected zone;

I Wiper smooths away surface problems

The Wiper feature illustrated shows a generic scrolled shoulder consisting of six equally spaced scrolls extending from the pin out to the edge or extent of the shoulder. The second illustration shows the same tool with a Wiper feature included. Essentially, the Wiper feature is the shoulder area located around the outer portion of a given shoulder face, which serves to limit the extent of the scrolls on that face. Incorporation of a Wiper feature on a given



shoulder face provides a smooth, continuous tool shoulder edge and compressive surface area. This is in contrast to the interrupted surface edge of scrolls extended to the



edge of a given shoulder face, with its alternating friction coefficient (alternating between aluminium-on-aluminium and tool material-on-aluminium).

Process innovations

High rotational speed friction stir welding (HRS-FSW) and fixed shoulders (zero rpm) are two of the innovations investigated at WSU.

Conventionally, weld tool rotational speeds in FSW are on the order of 200-2,000 rpm. However, it has been demonstrated that FSW can be performed at much higher spindle speeds (greater than 3,000 rpm). Related HRS-FSW work conducted by Crawford et al at Vanderbilt University showed that as rpm increases above 5,000 rpm the material flow dynamics change and appear to become more fluid.

The potential advantage of operating at higher rotational speeds is the ability to reduce spindle torque and forging loads. Ensuring defect-free welds (e.g. free of voids and wormholes) requires careful control of process parameters and tooling. One approach has been to include a non-rotating shoulder surrounding the rotating pin. The shoulder must be constructed such that it is able to maintain a sufficient forging load to prevent weld defects and the entrainment of weld flash between the probe and shoulder.

Investigation into HRS-FSW

The investigation at WSU into HRS-FSW was begun using a commercial electric router attached to a work table and manual feed. Testing continued on a FADAL VMC-4020 CNC milling machine equipped with a high-speed 30,000 maximum rpm electric spindle and a small liquid-cooled anvil.

A dynamometer was mounted under the anvil to measure welding forces.

Current work is being carried out on an MTS ISTIR PDS System equipped with a REGO-FIX spindle speeder.

In the initial study with the router, thin gauge 6061, 2024, and 7075 were welded using featureless probes with shoulders with concave angles ranging from 10-20 degrees. The study covered rotational speeds ranging from 6,000 to 24,000 rpm and travel speeds ranging from 1-20 in./min. Lead angles from 2.0 to 2.5 degrees reportedly produced the best welds. Joint strengths 60 per cent to 70 per cent of the parent material were achieved with failures typically occurring in the HAZ. A notable exception was a joint efficiency of 83 per cent that was achieved in 0.062-in. 2024-T3 aluminium sheet with greatly reduced processing loads.

Because of the tendency of HRS-FSW to produce weld flash and porosity, a weld tool with a probe surrounded by a fixed (non-rotating) shoulder was developed. Before the project was completed, a fixed shoulder design was developed which produced a sound, defect-free joint in 6061-T4 when welding at very low travel speeds of 0.25 to 1.0 in. per min.

A significant result was obtained in this weld. The outline of the pin and fixed shoulder are superimposed over the micrograph for reference. A secondary, or induced stir zone (ISZ) was shown to have formed to a depth nearly twice the length of the weld tool probe. In conventional rotational speed welding, the extension of the DXZ is much less than the length of the probe. Therefore, further work was conducted with HRS-FRW and fixed shoulders to better understand this metal flow phenomenon and to determine poten-

tial benefits of an ISZ that appears to mirror the DXZ.

Following further development of the fixed shoulder design, a weld was produced in 0.125 inch thick 7075-T73 at 600 rpm and 8 ipm.

The surface roughness along the centreline of the weld track, and against the direction of welding, was measured to be 5µin Ra, which was less than the parent material which measured 12µin Ra. These are compelling results and research is ongoing to develop robust fix-shoulder designs and process parameters.

Conclusions

Significant advances have been achieved and are ongoing in developing and evaluating FSW technologies, especially in the areas of materials, structures, weld tools, and process innovations. In materials development, when joining higher strength 7000 series aluminium alloys, post weld ageing is necessary to stabilise the microstructure in the friction stir welded regions.

The selected overaging treatments also improve corrosion resistance of these alloys. In structures development, FSSW holds promise for competing favorably with conventional joining technologies, such as riveting.

In tooling development, placing a continuous surface on a given scrolled shoulder improves surface roughness and in turn reduces the likelihood for fatigue to initiate in the central portion of the weld track.

In process innovations, HRS-FSW has been demonstrated to have the potential to create strong metallurgical joints with lower process forces than typically observed in FSW. A fixed shoulder also has an observable impact on the microstructure and resulting properties of the weld, especially by suppressing weld porosity and wormhole defects.

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