Development and Qualification of a Production Capable FSW Process for 25 mm Deep Robotic Friction Stir Welds

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Introduction

Friction Stir Welding (FSW) has been demonstrated to be a robust joining process in the laboratory and initial production applications involving joining of extrusions. However, as FSW transitions into applications requiring joining of multiple detail parts into complex assemblies, much less is understood about FSW's capability. In joining for complex assemblies it is much more difficult, impractical, or costly to achieve laboratory level control of manufacturing variables, such as joint gap, part mismatch, part location part thickness, part cleanliness, etc. that could potentially affect the weld quality. All of these considerations are important for the application of FSW and development of industry specifications and standards related to the process.

To understand these issues, a process development study was completed for an application involving the joining of multiple detail parts to form a large aluminum box assembly. The assembly required a multitude of one inch deep, multi-dimensional FSW welds. A review of the drawings related to the application indicated that laboratory type joint conditions (no gap, no joint mismatch, etc.) could not be guaranteed. Therefore the process development associated with the application required an understanding of how these production variables would affect the process. In this study a baseline process was first developed. Then a design of experiments (DOE) was performed to confirm that a stable process had been developed, varying rotation speed, travel speed, and welding force. After this was completed, a study was initiated to determine the stability of the process as a function of manufacturing process variables such as gap, joint mismatch, and part location. Additionally, other production related issues are discussed, including weld repair procedures. Another production related issue that is discussed is the potential for process modification after the start of production.

Development Process for a Production Capable FSW Process

For production applications, the development of a production capable process is typically a multi-step process. This is more in-depth and exhaustive than a laboratory development process. These steps can be summarized as follows;

1) Phase I: Development of a baseline process. In this initial phase of the welding process, nominal welding parameters are determined. These include rotation speed, travel speed, welding force, tool orientation, and tool design. In this phase of the development a series of welds are created with a specific tool design. Various testing procedures are then used to determine the weld quality. These testing procedures typically involve destructive testing, but can also include non-

destructive testing procedures. The most common destructive testing procedures are tensile testing, bend testing, and cross-section analysis. If an acceptable process is developed as determined by testing results, then Phase II is initiated. If an acceptable process is not achieved, then the tool design or welding parameters are modified until an acceptable baseline process is developed.

2) Phase II: Performance of a Design of Experiments (DOE). The DOE is intended to determine the stability of the nominal welding process by varying the critical welding parameters; travel speed, welding speed, and welding force (or tool position) about the nominal parameters. A typical DOE would include variation of plus 10%, minus 10%, and nominal conditions for each of the parameters. These welds are typically made at ideal welding conditions, i.e. no gap, no mismatch, part location exactly as desired. Each of the welds made for the design of experiments is also tested (tensile, bend, etc.) similar to what was done for the baseline process development. The results are then analyzed. If the process is deemed stable, by evidence of consistent results of the range of welding conditions, then Phase III is initiated. If the baseline process is shown to be unstable or near the edge of desirable operating conditions, the ‘nominal’ parameters are adjusted and the DOE can be repeated at the altered nominal conditions.
3) Phase III: Sensitivity to Production Process Variables. During this phase, the nominal welding process is used to make welds at various gap conditions, joint mismatch, part location settings, and part cleanliness. The goal of this phase is to ensure that the developed process is not sensitive to variations that may be experienced in production. This typically requires pre-review of welding and part drawings to determine what typical levels of variation can be anticipated. If unacceptable variation of weld quality occurs as a result of the production variable change, then the process is modified or a review of the inbound parts is made to determine if the variation of interest can be reasonably reduced.
4) Phase IV: Development of a Repair Welding Process. In many applications a welding repair procedure may be required. A repair could be necessitated as a result of many things, including but not limited to FSW tool failure, power outage, sensor failure, etc.
5) Phase V: Process Modifications after Start of Production: It maybe necessary to modify welding conditions after production has begun, regardless of how much work is put into the process development phases. Unexpected part variation and high rates of tool pin failure or tool wear are some of the issues that may justify a need to modify the process after production is initiated. Items such as tool pin failure or wear may not be known until production is initiated, especially if experience with the particular alloy or joint configuration is limited. .

Baseline Process Development

To develop a baseline process, a review of the application is generally performed first. The application of the subject of this paper had the following characteristics:

1) Required welds of a minimum of 25.4 mm (1.0”) penetration in 6061-T6 Aluminum.
2) Partial and full penetration welds were required.
3) Multi-dimensional welding was required.
4) Weld gap conditions of up to 1 mm could be experienced (after review of tolerances)
5) Surfaces were to be machined, so joint mismatch was restricted to less than 0.25 mm
6) Fixture and detail part tolerances indicated part/seam locations could vary up to 2 mm
7) Part thickness could vary up to 0.5 mm, but with partial penetration welds thickness variation was not a significant factor.
8) The application had minimal weld strength safety factor and part had high value. Thus scrapping the part was not an option, if any issues occurred. This indicated that a weld repair procedure was required for tool pin failure and inadvertent stoppages (power outages, machine failure).
9) The application did not allow for pre-drilling of starter holes. Thus, the process must plunge into unprocessed material.

The first step in the process development is to develop a baseline process. The inputs to this process dictated that a robotic solution was required, due to the multi-dimensional nature of the application and the relatively low-overall volume (i.e. a custom built multi-axis machine could not be justified). This dictated that the process loads were limited to about 2500 lbs of thrust force, less than 1000 lbs traverse force, and about 10 kW of rotary spindle power.

From this input, a FSW tool was designed and initial weld parameters estimated. Initial welds were made in the fixture and setup shown in Figure 1. Initial welds resulted in forces that were too high and clogging of the tool. This indicated that the tool design needed to be modified and weld parameters changed.

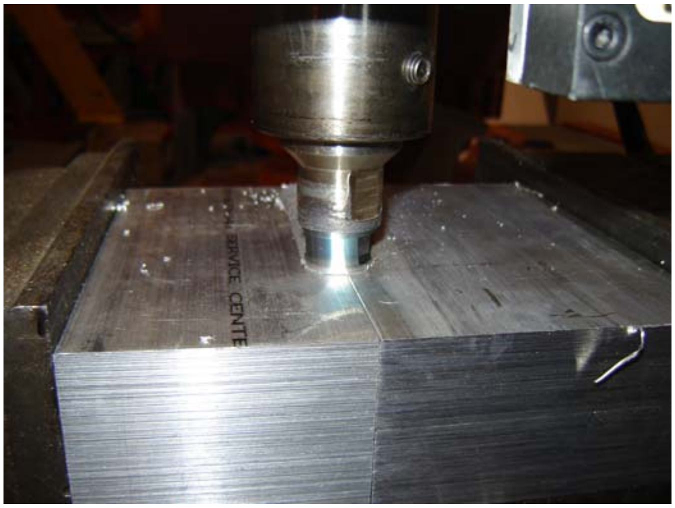

Figure 1: Robotic Process Development Fixture

Modifications to the FSW tool and parameters were made, and then a series of welds were made over a range of welding parameters. All of these welds were tensile tested and a few were wrap-around bend tested and cross-sectioned. The bend test was a side-bend test, due to the material thickness being in excess of 9.5 mm (3/8”). The results of typical tensile and side-bend tests are shown in Figure 2. The bend tests passed and the tensile tests resulted in failure in the heat-affected zone (HAZ) with ultimate strengths of approximately 205 MPa (30 ksi).

Figure 2: Typical Tensile and Side-Bend Tests from Baseline Process Development

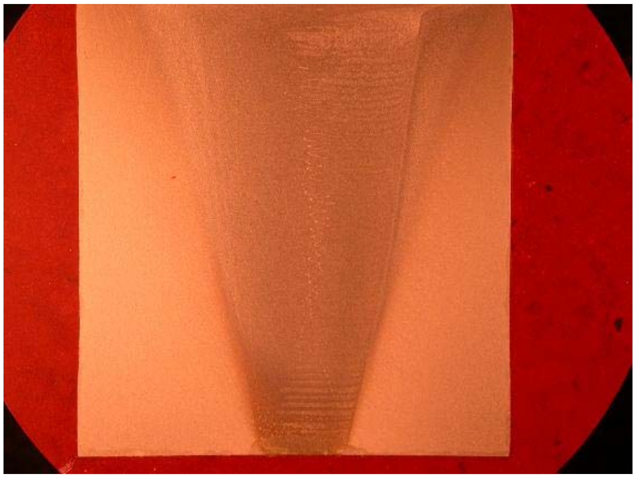

Figure 3: Cross-Section of 1” Partial Penetration 6061-T6 FSW etched with Sodium Hydroxide

Design of Experiments: Baseline Process Stability

Once an acceptable baseline process was developed, the next step was to determine the stability of the process by varying the critical parameters about the nominal parameters previously defined in the baseline process development. A design of experiments (DOE) was created to modify the rotation speed, travel speed, and welding force about the nominal parameters by approximately +-10. There were three settings of each variable.

Welds were then created at the settings for each variable. All of these welds were tensile tested and a few were side-bend tested and cross-sectioned. The ultimate tensile test results were then plotted to determine any sensitivity of weld strength to any of the critical welding parameters. These charts are shown in Figures 4, 5, and 6. The charts indicate the average tensile strength at each of the settings and the standard deviation. The charts indicate that there are no significant effects of any of the three critical variables on the weld strength, and no significant variation in strength (standard deviation < 10 MPa). Thus a stable process had been achieved. If significant variation in weld strength versus any of the variables had been observed, then the data would be reviewed and nominal parameters or tool design modified.

At this point, weld parameter sheets (WPS) and procedure qualification records (PQR) were generated to reflect acceptable nominal welding parameters.

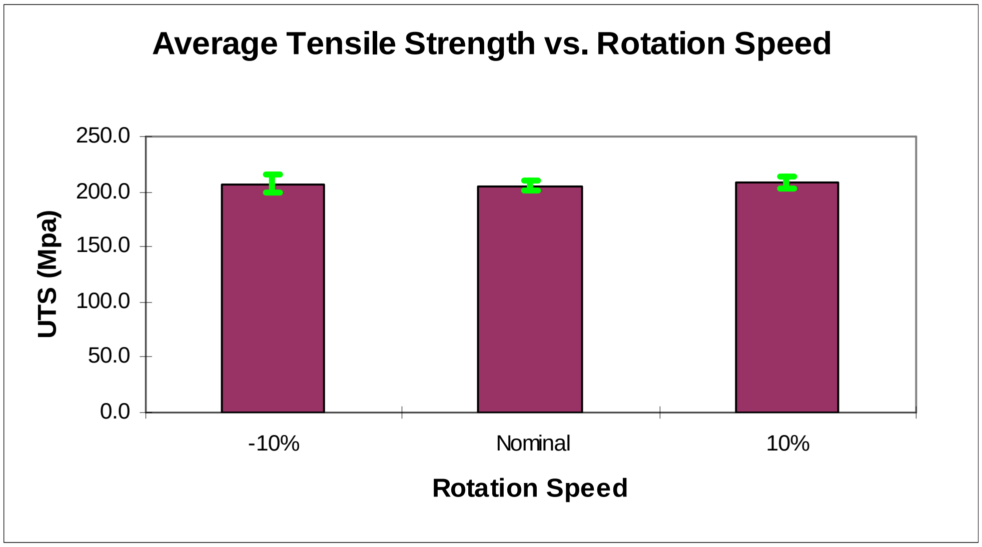

Figure 4: Average Tensile Strength vs. Rotation Speed

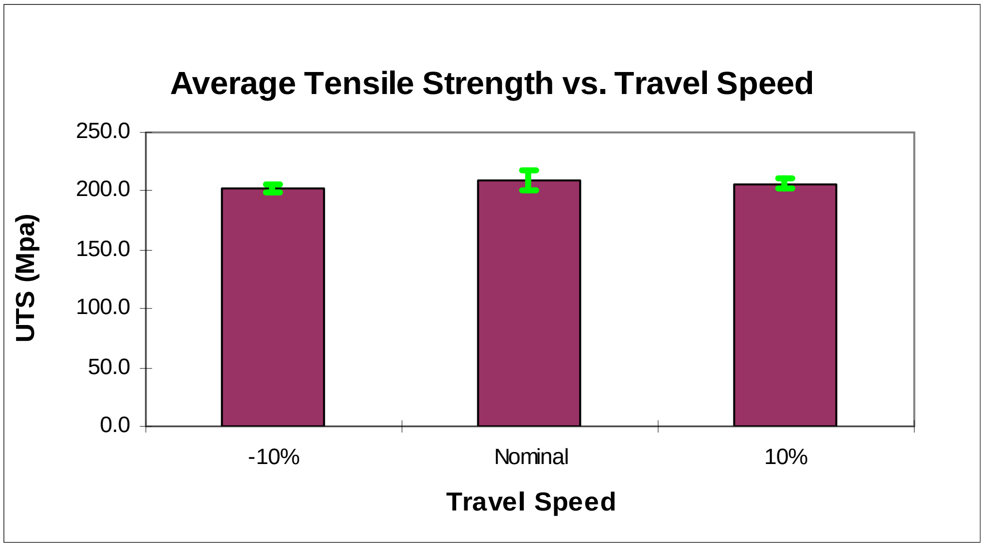

Figure 5: Average Tensile Strength vs. Travel Speed

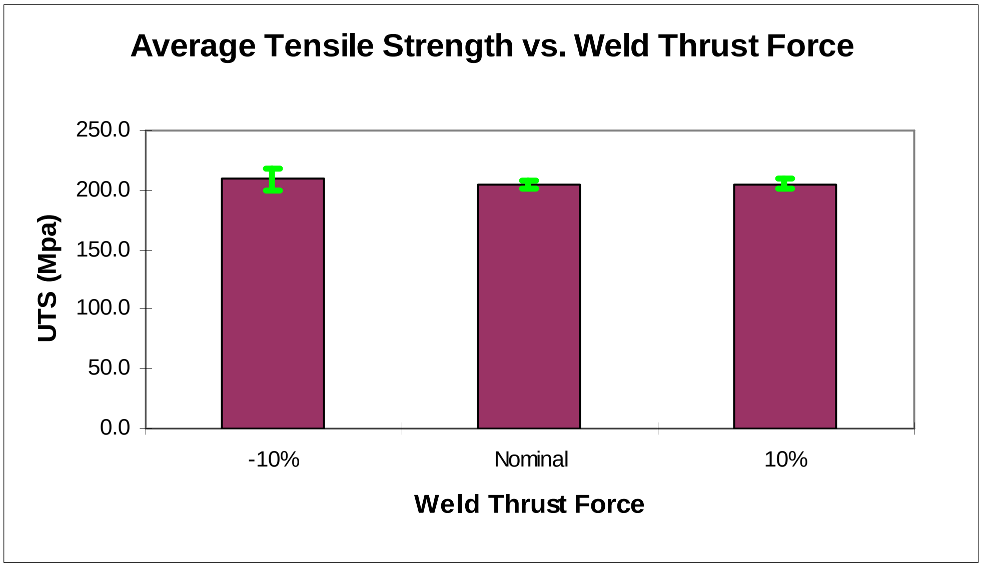

Figure 6: Average Tensile Strength vs. Welding Thrust Force

Sensitivity to Production Variables (Gap, Part Location, etc.)

In production applications, gap conditions, part location, part thickness, and joint mismatch typically cannot be controlled to the laboratory level or initial process development level tolerances. Therefore it is important to understand the effects of these production variables on the FSW process. In this particular application, studies were conducted to vary joint gap and part location with respect to the centerline of the FSW tool. Studies involving other production issues, such as part thickness, joint mismatch, and part cleanliness variation were deemed to be unnecessary. This was due to pre-processing of the part which would guarantee these conditions would not be seen in production. Thus, studies were not conducted to examine the consequences of these inputs. However, this type of part control may not be present in other applications, and consequences of these inputs may need to be investigated.

For this application, a part gap study was performed by varying the gap conditions from 0 to 1 mm in 0.25 mm increments. The welds were then tensile tested. The results are shown in Figure 7. For both the full and partial penetration welds there were no significant detrimental results up to a 1 mm gap.

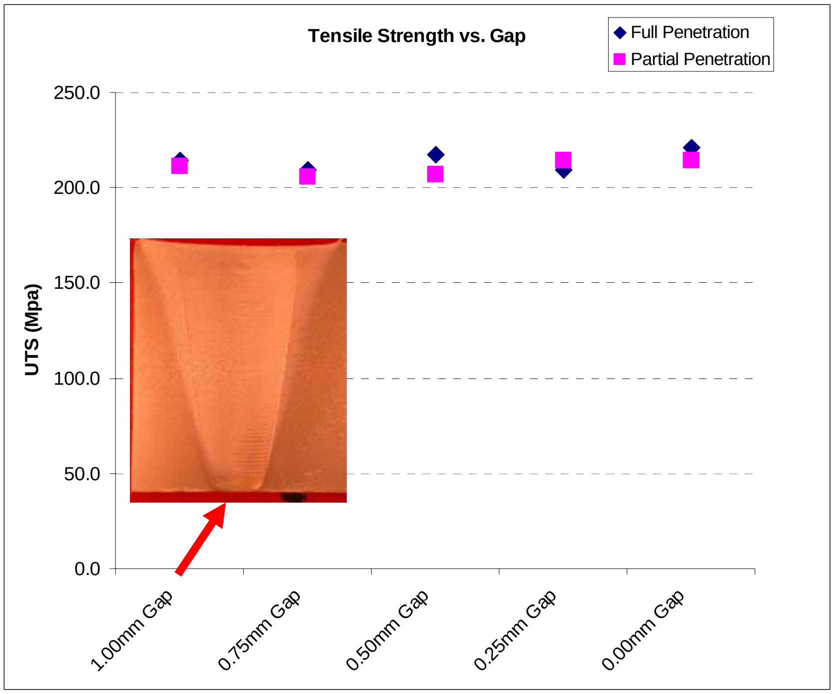

Figure 7: Tensile Strength vs. Gap Condition and Cross-Section of Weld with 1 mm Gap

It should be cautioned that these results are for this particular alloy, particular tool design and weld parameters. Alternate configurations and setups could have much more significant variation of results with respect to gap conditions. As an example, a zero degree tilt FSW tool was tested for its gap sensitivity in this study. The tool had an identical pin, but the shoulder was modified with features that are typically used for zero degree tilt. In this case, as the gap increased about 0.5 mm, a surface void appeared. This significantly affected tensile strength of the weld. These results indicate that zero degree tilt solution, though acceptable in a laboratory environment, must be used with considerable caution in a production environment. Figure 8 shows the tensile test results with varying gap conditions using a zero degree travel angle FSW tool. Figure 9 shows the visual and cross-section results of the same welds. On the left is a weld having a 1 mm gap condition that results in a large surface void and lack of consolidation. On the other hand, at zero gap, acceptable weld quality results as is demonstrated in the photograph on the right hand side of the figure. The tensile test results are also acceptable with zero gap as is shown in Figure 8.

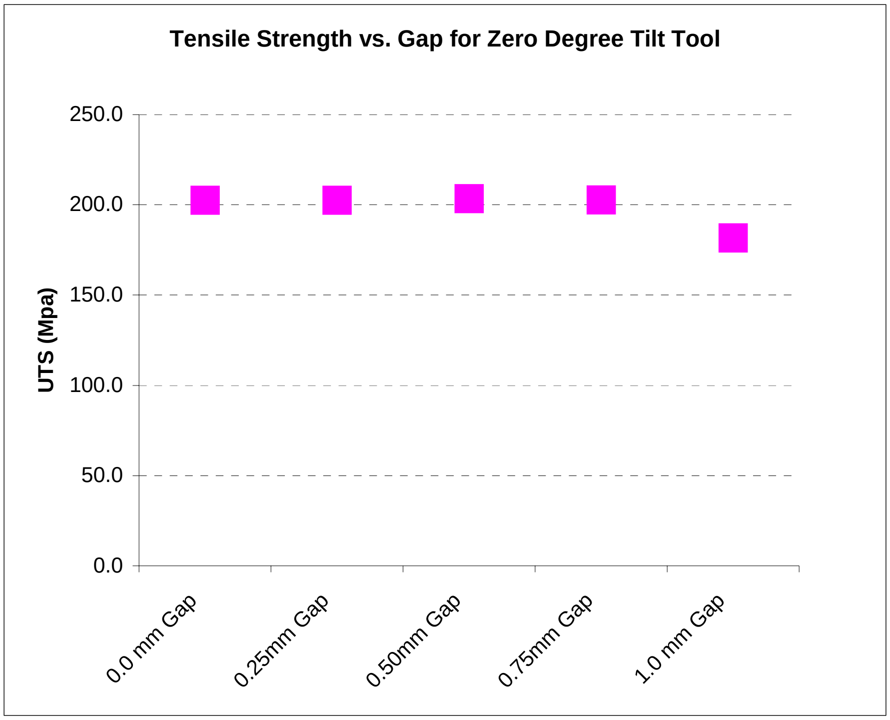

Figure 8: Tensile Strength vs. Gap Condition for Zero Degree Travel (Tilt) Angle

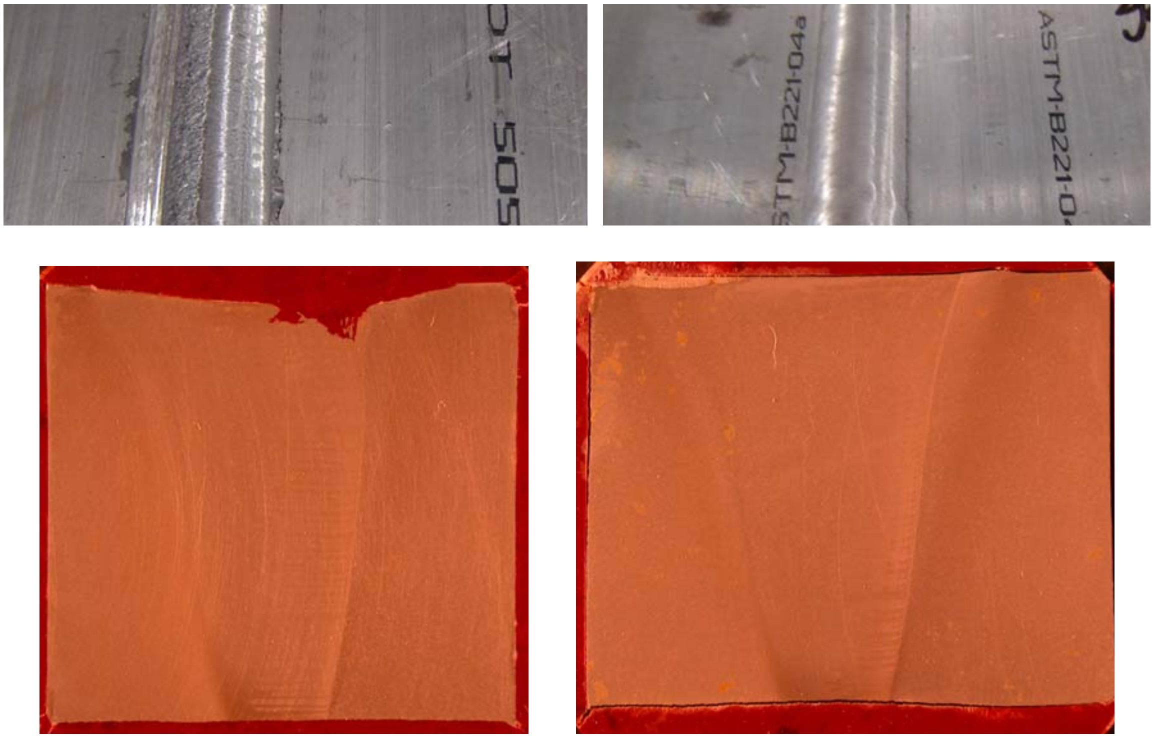

Figure 9: Visual Weld Results with 1 mm Gap (Left) and Zero Gap (Right) using Zero Degree Travel Angle FSW Tool

The other testing that was performed was to determine weld strength as a result of varying part location, to mimic conditions where the FSW tool was not centered along the seam. In this case, the part was moved plus or minus a total of 135% of the minimum pin radius. The results are shown in Figure 9. These results indicate that the weld strength as a result of the production variation in part location is not symmetric. If the joint line is on the retreating side of the FSW tool, then the loss in strength is more dramatic than if the joint line is on the advancing side of the tool. This indicates that there is more material motion in the advancing side of the FSW tool. It can be seen in the cross-sections (in the figure) that the original joint line remnant is much more visible when the joint line falls on the retreating side of the tool versus the advancing side of the tool. In this particular application, it indicated that ability to modify the welding path for each weld was required to overcome the variation that could be seen in part location.

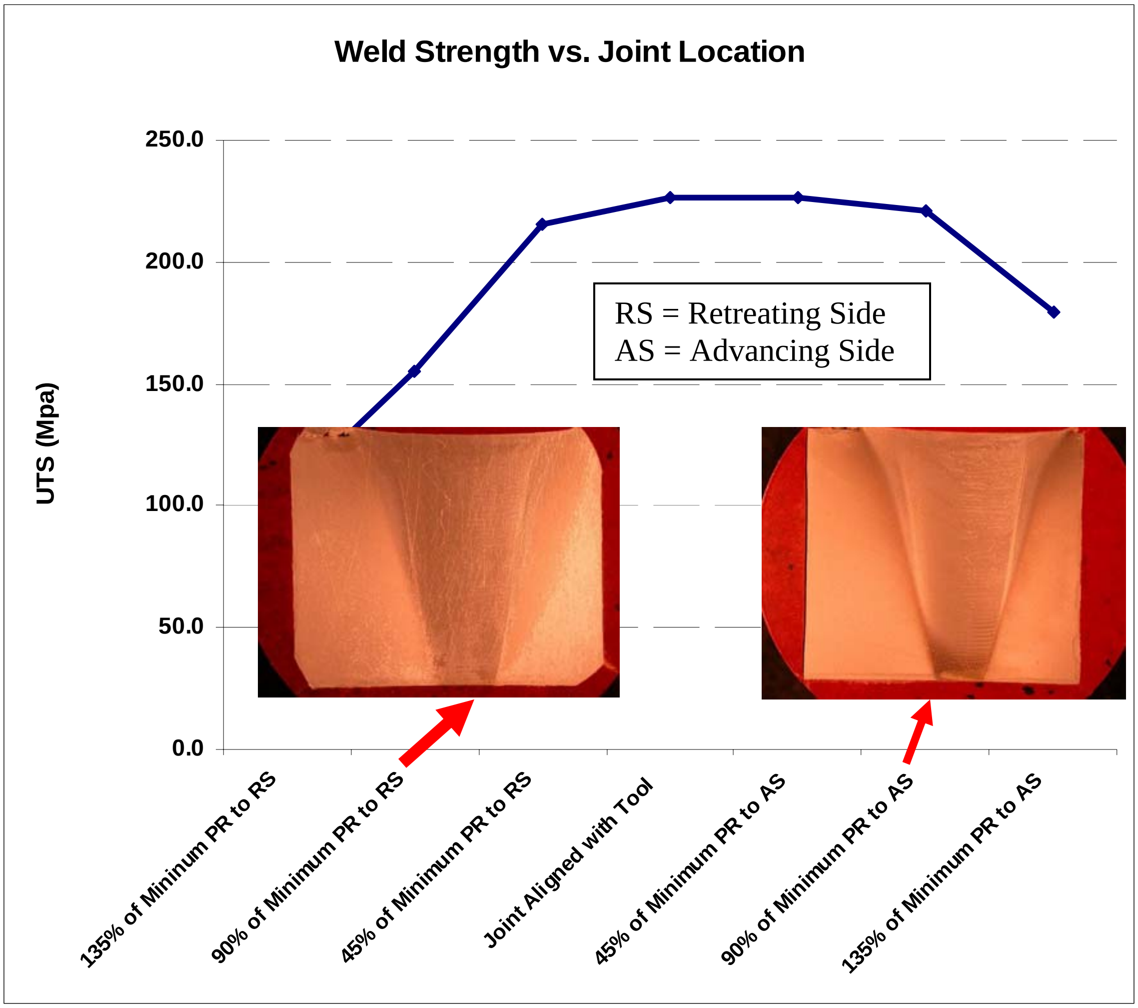

Figure 9: Tensile Strength vs. Joint Location and Cross-Sections with Joint Misaligned

Development of a Repair Welding Procedure

In applications where the cost of rework or repair costs is less than the cost of scraping the part, a welding repair process is required. Repair or rework welding processes could be required for the following reasons;

1) Tool pin failure during a weld
2) Power outage or other inadvertent stoppage of machine
3) Unacceptable weld quality (e.g. surface void), due to sensor failure, etc.

In these cases, the repair procedure must allow for the final properties to attain the desired properties. If this cannot be done, then the part would need to be scrapped.

For the tool pin failure and inadvertent stop, the repair procedure can be similar. In either case, one potential repair procedure is to place a plug (of the same base material) in the exit hole left at the stop location and then reweld over the plug. To fully mix the plug and create an optimal strength joint, the repair process must include three passes. The passes are typically on the same joint line and then shifted to the left and right of the original joint line.

For this particular application, the repair procedure was simulated in similar test blocks as the remainder of the process development. The welds were tensile tested to determine any affects of the repair process. In this particular case, the internal quality of the weld was acceptable, as seen in Figure 9 showing a cross-section of the weld. The tensile strength of the weld was approximately 10% lower than the single pass weld, most likely due to the additional heating affects of the multi-pass repair process.

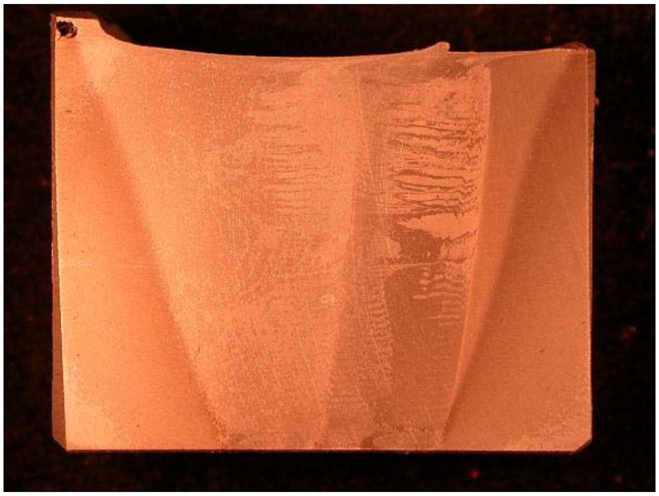

Figure 9: Cross-Section Thru Repair Area

Other repair procedures can also be considered including

1) GMAW plug welds,
2) Rotary friction plug welds,

3) A process where the same plug is used but only a single pass FSW is made.
4) FSW over area of stoppage without a plug (likely to leave internal voids)

With most of these alternate cases, it is likely that the final weld properties will be less than the weld properties as generated by the three pass procedure described above. But, given the requirements of the product, these other procedures could be acceptable and can be less costly. In the end, the product requirements and associated specifications need to be considered to help determine an acceptable repair procedure.

Process Modifications after Start of Production (Tool Life)

After completion of the process development there are a few unknowns that remain to be discovered. The most significant unknown is tool life. Tool life is indicated by the amount of time or distance of weld the FSW tool lasts before pin failure occurs or unacceptable amounts of wear occur. Once production starts it maybe determined that tool life is unacceptably short. If this occurs, then the tool design may need to be modified.

On the other hand, it can actually be deemed that the tool life is too long. One may enquire as to why this is an issue. This conclusion can be generated if the tool is too large. If the tool is too large, then travel speeds can be limited. Slower travel speeds limit productivity and increase cost. In addition, large tools increase loads being placed on the FSW machine, increasing required power and increasing wear rates on machine components, further affecting cost. Thus, an ideal FSW tool will be optimized to minimize overall production cost, with a balance between failure rate and optimal productivity.

However, production experience helps to mitigate the need to modify FSW tools. With experience, these modifications should be minimal and if all of the process development work was successful, then any changes should not affect the process significantly.

Conclusions

A production capable FSW process has been developed for a 25.4 mm penetration butt weld in 6061-T6 Aluminum alloy. The process was developed specifically for robotic welding application, since many of the weld paths are multi-dimensional. This process has been used in production for the last year to assemble and join complex assemblies with approximately 15 meters of weld per assembly. The following conclusions have been drawn from this work

1) Robotic FSW machines using standard industrial robots are capable of creating welds with penetrations up to one inch. This is a significantly higher depth of penetration than previously thought possible.
2) Low welding force processes (< 10 kN thrust force) can be developed for material 25 mm in thickness.

3) A stable FSW process was developed that could withstand in excess of 10% variation from nominal operating condition of the critical parameters (rotation speed, travel speed, and welding thrust force).
4) The developed process was shown to be stable with gap conditions ranging from 0 millimeters up to 1 millimeter.
5) It was shown that zero degree tilt FSW tools must be used with caution in production applications due to sensitivity to gap conditions.
6) Pre-drilled starter holes are not necessary for welds with up to 25 mm penetration.
7) A repair process was developed that involved plugs and multi-pass welding with less than a 10% loss in tensile strength
8) The FSW process is more sensitive to part mis-location on the retreating side of the FSW tool. This has significant ramifications for FSW process control and specifications and needs to be considered in these documents.

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References

1. Thomas, W.M. et al, Friction Stir Butt Welding, U. S. Patent No. 5,460,317.
2. “Process Specification for Friction Stir Welding”, NASA PRC-0014, Revision B, January 2005.
3. Smith, C.B., “Friction Stir Welding using a Standard Industrial Robot”, Proceedings of the 2nd International Symposium on FSW, June 2000.
4. Hinrichs, J.F. and Smith, C.B., “Friction Stir Welding - Lean, Mean and Green Welding Process”, AWS Detroit Sheet Metal Conference, May, 2004
5. Strombeck, A.V., Shilling, C., and Dos Santos, J.F., “Robotic Friction Stir Welding – Tool Technology and Applications”, Proceedings of the 2nd International Symposium on FSW, June 2000.
6. Smith C. B., Hinrichs, J. F., and Crusan, W. A., “Robotic Friction Stir Welding – The State of the Art”, Proceedings of the 3rd International Symposium on FSW, May 2003.
7. Smith C. B., Hinrichs, J. F., and Crusan, W. A., “Friction Stir Welding Stirs Up Process Competition”, Forming and Fabricating, Feb. 2003