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LOADING CONSIDERATIONS FOR IMPLEMENTING FRICTION STIR WELDING FOR LARGE DIAMETER TANK FABRICATION

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Introduction

The main objectives of the research presented here are to determine the reaction loads associated with friction stir welding (FSW) and to determine the suitability of an existing welding fixture for implementing this welding process in the fabrication of large diameter tanks. Friction stir welding is a relatively new process which is being investigated as a method for joining aluminum alloys. The aluminum-lithium alloy, Al-Li 2195, which is being used to fabricate the super-light-weight shuttle external tank has proven difficult to join using fusion techniques. Therefore, FSW and its potential applicability to joining Al-Li 2195 are of particular interest to NASA.

A schematic of the process as applied to welding an Al-Li 2195 butt joint is shown in Figure 1. The process will be described in reference to this type of weld. The main components required to conduct the friction stir weld include the pin tool, the anvil (backing bar) and the plates to be welded. The pin tool consists of a hardened steel tool with a large diameter shoulder and a smaller diameter threaded probe. The anvil is a flat, rigid steel plate. The aluminum plates which are to be joined are rigidly clamped to the anvil to prevent lateral movement and deflections relative to the anvil. The pin tool is rotated at approximately 300-400rpm and tilted at a lead angle of approximately 2.5 degrees to the plates. When the FSW process is initiated, the pin tool is not in contact with the plates. The pin tool is then plunged into the plates such that the trailing edge of the shoulder is approximately 0.006 inches below the top surface of the plates. The dimensions of the pin tool are such that in this position, the probe of the pin tool is approximately 0.002 inches above the top surface of the anvil. The friction stir weld is completed by traversing the weld seam at a travel speed of approximately 4 inches per minute.

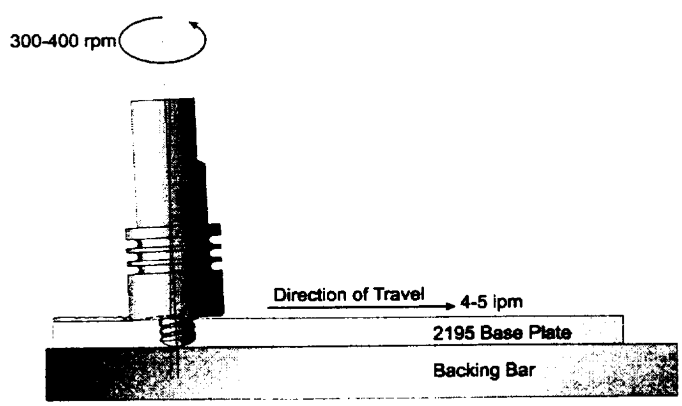


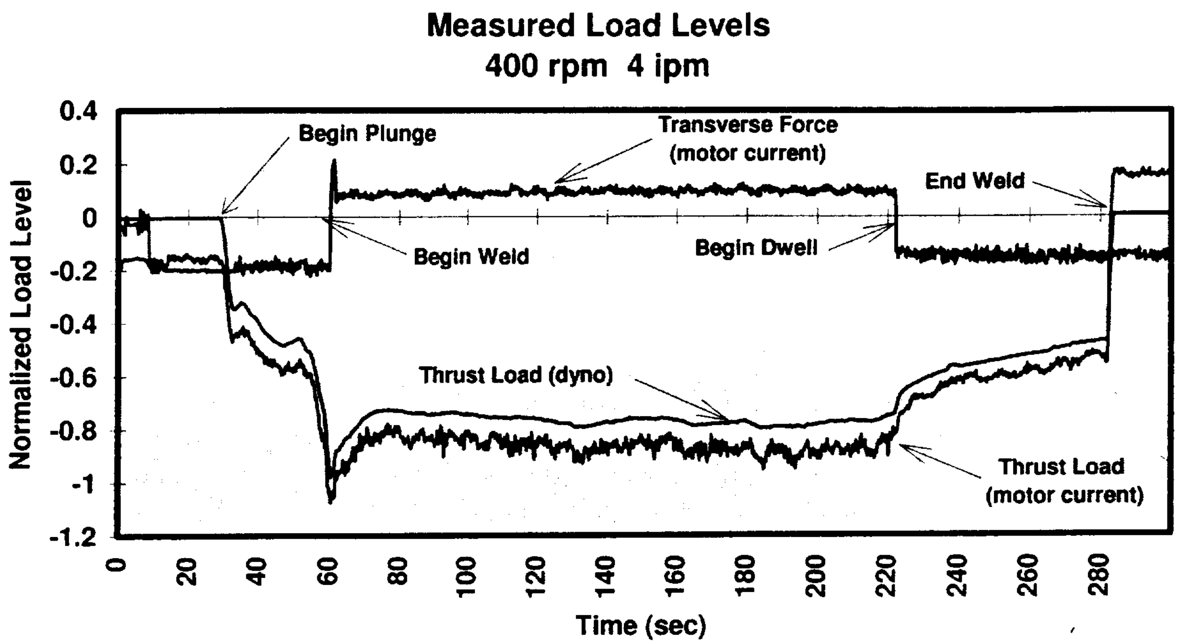
Figure 1 Schematic of friction stir welding process.

The exact mechanisms which define the friction stir welding process are not completely understood. However, FSW is best described in conventional processing terms as a combination of extrusion and forging. The threaded probe shears and plasticizes the material in the region near the probe. This plasticized material is extruded around the circumference of the probe and between the probe tip and the top surface of the anvil. This extruded material is then forged between the shoulder and the anvil as it reaches the heel of the shoulder.

There are several advantages of FSW as compared to fusion welds when applied to joining many aluminum alloys. The most significant of these is that FSW appears to be a solid state process. Although the material temperature increases to the point where the aluminum becomes plastic, it does not reach the melting point. The phase change which occurs with fusion welds of Al-Li 2195 cause problems in the resulting microstructure and tend to reduce the overall joint efficiency. Since FSW is a solid state process, some of these problems can be avoided. Other advantages of FSW are the limited number of process parameters which must be controlled, and the relatively minor amount of weld preparation which is required. However, there are also several disadvantages to the FSW process. These disadvantages include the key-hole which remains at the end of the weld when the pin tool is extracted, the reduced travel speed as compared to typical fusion welds, the tolerances with which the pin tool, weld material and anvil must be located relative to one another, and the tooling and fixtures required to react the forces produced during friction stir welding. The reaction loads and associated tooling requirements are addressed here. In a typical fusion weld, the welding head is not in direct contact with the workpiece and produces no reaction loads between the weld head and the workpiece. Therefore, the fixture for a fusion weld is required only to maintain the workpiece in its proper position and provide the needed movement of the weld head. However, the magnitude of the reaction loads between the weld head and the workpiece are significant in a FSW. These reaction loads cause deflections in the fixture which must be accommodated in the process control in order to maintain accurate location of the pin tool.

Reaction Load Measurement

A laboratory set-up was used to measure the reaction loads in a typical FSW butt joint. A 5-axis horizontal boring mill is the foundation for the set-up. An anvil was fabricated and fixed to the mill bed. The anvil is used to rigidly clamp plates configured in a butt weld position. The pin tool is held and rotated by the spindle while one of the mill axes is used to obtain the desired lead angle between the pin tool and the material. Two methods were used to determine the reaction loads during the welding process. An indirect measurement was established using measurements of the motor current for each axis of the mill. Load cells were used to establish calibration curves for converting current to force. The motor currents were measured during the weld process and converted to forces using the calibration curves. More recently, a rotating dynamometer was used to directly measure the reaction loads during the welds. The dynamometer serves as a tool holder and interfaces the pin tool with the spindle. The dynamometer is capable of directly measuring 4 separate loads, forces in the x,y,z directions and torque on the z axis. The z coordinate is collinear with the rotating axis of the dynamometer and measures the thrust load on the pin tool. The x and y coordinates provide a rotating reference plane whose normal is the z axis and are used to measure the transverse force in the direction of the weld seam. A typical set of measurements is shown in Figure 2. The absolute magnitude of the forces is not shown due to confidentiality agreements. However, the forces are accurately represented in a qualitative sense.



Good agreement was obtained between the indirect measurements using the motor currents and the direct measurements using the rotating dynamometer. This is significant in that it allows future analysis of motor current data which was acquired before the dynamometer measurements were available. The weld data plotted in Figure 2 begins with the pin tool initially at some offset distance from the material. At approximately 30 seconds the pin tool begins to plunge into the material. The magnitude of the thrust load reaches a maximum at the end of the plunge. The magnitudes of the transverse force along the weld seam and the thrust load on the pin tool remain essentially constant during the weld. At the completion of the weld, the pin tool is allowed to dwell for 60 seconds without traveling along the weld seam before it is extracted. This is not typical but was done in order to acquire data for development of models of the welding process.

The torque, not shown here, also remains essentially constant during the weld and decreases during the dwell period at the end of the weld. Depending upon the weld parameters, plots of the torque have demonstrated a combination of high frequency components superimposed on low frequency components. The source of these components is not currently understood.

Deflection Measurements

In order to implement the friction stir welding process for fabricating large diameter tanks, the effect of the reaction loads on fixtures and tooling must be determined. The current investigation involves modification of a vertical weld tool (VWT). The VWT is designed for conducting longitudinal fusion welds of tanks ranging from approximately 8 feet to 14 feet in diameter and approximately 16 feet in height. This fixture was designed to support the articles being welded. It must be determined if the VWT can support the reaction loads associated with friction stir welding. The main load of interest is the axial thrust load directed along the pin tool axis. In order to successfully implement friction stir welding on the VWT, the fixture must be rigid enough to maintain the accurate positioning of the pin tool, weld material and anvil. Using the load measurements discussed above, design loads for implementing FSW were determined. Deflection measurements of the VWT were made using these design loads. The measurement technique and results are discussed here.

The VWT consists of several stanchions designed to locate and hold barrel sections of a tank for welding. A cylinder is fabricated by completing a succession of welds to join barrel sections. Four columns are located at the position where the barrel sections are joined. These four columns are designed to accurately locate the barrel sections while a fusion weld is conducted. The cross section of each column is the same and they are located symmetrically about the centerline of the weld. A plan view of the four columns, Figure 3, includes an observer tower located near the columns and a schematic of the loading arrangement used to obtain deflection measurements.

The implementation of FSW on the VWT requires a welding head to be mounted on a carriage which travels vertically on rails along the length of the two columns located on the south side. The carriage motion will be accomplished via two rails attached to the two columns on the south side. An anvil will be located across the two columns on the north side and will extend the length of the columns. The material to be welded will be located between the anvil and the welding head. A loading device was designed to simulate the reactions associated with this FSW implementation. A beam was attached across the two south columns, with the attachment points located at the proposed position for the FSW carriage rails. A load cell extends from this beam to an anvil attached to the two north columns. This load cell consists of a hydraulic actuator with pressure regulation capabilities. With this loading arrangement it is possible to simulate the thrust loads associated with the planned FSW implementation. The loading device was located at 5 separate positions vertically along the length of the fixture. At each position the fixture was loaded to 25%, 50%, 75% and 100% of the design load.

The main objectives of the measurements were to determine the relative deflection between the north and south columns at the weld seam and to determine the absolute deflection of the south columns near the proposed location of the carriage rails. Measurements of the relative deflections are important for determining the amount of position compensation which will be required by the weld head / carriage arrangement to successfully conduct FSW over the length of the fixture. The absolute measurements are important to determine if the columns are rigid enough to prevent the carriage drive mechanism from binding as it travels the length of the weld. In Figure 3, the circles indicate relative deflection measurement locations and the diamonds indicate absolute deflection measurement locations. All measurements were made with digital dial indicators accurate to within ± 0.00005 inches. The relative measurements were obtained by measuring the deflections between the north and south columns at the locations shown. The absolute deflections were obtained using the observer tower as a reference since it was unaffected by the loading.

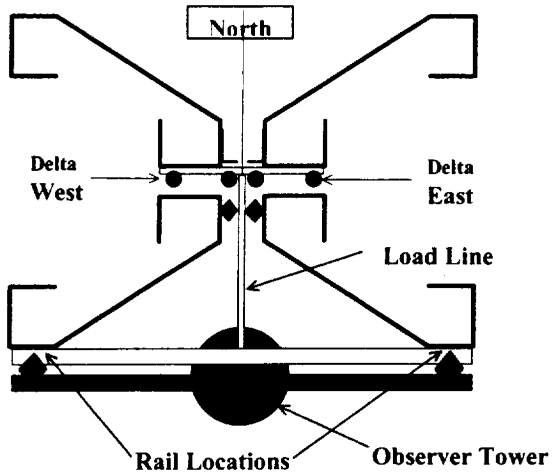


Figure 3 Plan view of the VWT weld station columns

The maximum absolute deflections of the south columns measured at the rail locations was 0.030 inches. In addition, the absolute deflections of the column located in the south west quadrant and the column located in the south east quadrant differed by less than 0.010 inches. The maximum relative deflection measured near the weld centerline was 0.047 inches. However, the relative deflection of the columns on the west side and the relative deflection of the columns located on the east side differed by as much as 0.030 inches. This difference may be difficult to accommodate during a friction stir weld. This difference in deflections is believed to be due to the fact that the top of the columns are joined by a bolted connection. A more rigidly designed connection may need to be designed to replace the existing bolted connection. With this modification, the measurements indicate that the fixture is adequate for conducting FSW.

Conclusions

The FSW process seems to have many advantages over typical fusion processes for joining aluminum alloys. However, the reaction loads associated with FSW must not be overlooked. The quality of the weld produced by FSW is directly dependent upon the accuracy with which the pin tool, material and anvil are positioned relative to one another. Small deflections in fixtures can have adverse affects on weld quality. Fixtures designed for fusion welds should be tested to determine their rigidity when modifications are planned for FSW implementation.

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