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Friction Stir Weld Tooling Development for Application on the 2195 Al-Cu-Li Space Transportation System External Tank

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Abstract

Friction Stir Welding (FSW) is a new and innovative solid-state joining process which can be applied to difficult-to-weld aluminum alloys. However, the large forces involved with the process have posed a production tooling challenge. Lockheed Martin Michoud Space Systems has overcome many of these challenges on the Super Lightweight External Tank (ET) program. Utilizing Aluminum-Copper-Lithium alloy 2195 in the form of plate and extrusions, investigations of FSW process parameters have been completed. Major loading mechanisms are discussed in conjunction with deflection measurements. Since the ET program is a cryogenic application, a brief comparison of cryogenic material properties with room temperature material properties is offered for both FSW and fusion welds. Finally, a new approach to controlling the FSW process from a load perspective is introduced. Emphasis will be put on tooling development, as well as the impact of tooling design and philosophy on Friction Stir Weld success probability.

Introduction

The demand for greater lift capacity in launch vehicles has initiated the development of light, strong materials. One of the latest materials being used for its excellent strength-to-weight ratio is Al-Cu-Li 2195. Although there are many advantages associated with this alloy, fusion welding the alloy is difficult. Friction Stir Welding has proved to be one process for joining this alloy successfully and efficiently[1]. However, the nature of the process requires substantial forces. These forces can be characterized, understood and manipulated to meet tooling requirements while still producing acceptable weld quality.

There are two major mechanisms which determine the load within the system: tool geometry and process parameters. The force needed to plunge a friction stir weld tool below the surface of the material is directly proportional to the pressure seen under the heel of the tool. This introduces the first of two contributors to load in the system: tool geometry.

It has been shown through experimentation that larger diameter tools produce more load in the system than smaller diameter tools. Although exceptions to this rule have been seen by varying FSW tool geometries, namely pin height, it remains a general observation that larger overall tool geometries will require more force to meet a desired shoulder plunge depth. Exceptions have been observed in cases where the pin height was several thousandths of an inch shorter than normal. In these cases, the shoulder of the FSW tool had to be "overplunged" into the surface of the test panel to maintain a given pin-to-anvil distance, hereafter referred to as ***penetration ligament***. As a result, a reduction in weld thickness as well as excessive flash on either side of the weld footprint occurred.

The second mechanism that determines the load within the system is process parameters. Tool rotation, travel speed, penetration ligament, plunge rate and tool attack angle all have varying roles in determining the load reacted throughout the machinery. Since the attack angle has not been investigated within the scope of this text, it shall be omitted as a variable process parameter.

Early on in the development at Lockheed Martin Michoud Space Systems a Cincinnati milling machine was modified to produce friction stir welds. Panels up to 24-inches in length could successfully be joined, and accurate measurements of tool depth could be determined. Welds were made in the flat position on a movable, rigid table (anvil). As the need to demonstrate the process on production-scale hardware grew, a Niles gantry utilizing a 27-foot diameter turntable became the next friction stir weld tool[2]. All welds were made in the vertical position using a fixed head and anvil geometry. Currently, a modified 15-foot vertical weld tool at the Marshall Space Flight Center is being used to produce friction stir welds on full-scale hardware[5].

Most of the friction stir weld development on the Niles gantry was driven by Lockheed Martin's Hybrid Friction Stir Weld Program. This program was initiated as a potential solution to mitigate ET fusion welding problems. "Hybrid" is the term used to designate a friction stir weld made over an existing fusion weld[2]. Not all of the original cast structure of the fusion weld is consumed by the friction stir weld, therefore, hybrid friction stir welding has thus far been considered a partial penetration FSW process.

Both the Cincinnati milling machine and the 15-foot vertical weld tool have been employed mainly for "autogenous" friction stir weld development. "Autogenous" is the term used to designate a weld made on virgin material that has not been joined prior to friction stir welding[3]. In this text "autogenous" shall also apply to panels that have been tack welded by a solid-state process.

Discussion

Machinery & Deflection - It's impossible to adequately talk about loading a structure without discussing deflections. Since appreciable effort is exerted to control the depth of the pin tool, deflection within the system is important to understand if control of the penetration ligament is desired (except in the case of controlling through load, as described later). The Cincinnati milling machine proved to be a reliable, and more importantly *repeatable*, producer of deflection. All of the total deflection was measured on the spindle head as shown in Figure 1. The anvil, which was a moveable table, essentially had no displacement under load. The head was extended to the same location for every weld in order to maintain the moment necessary to produce repeatable deflections.

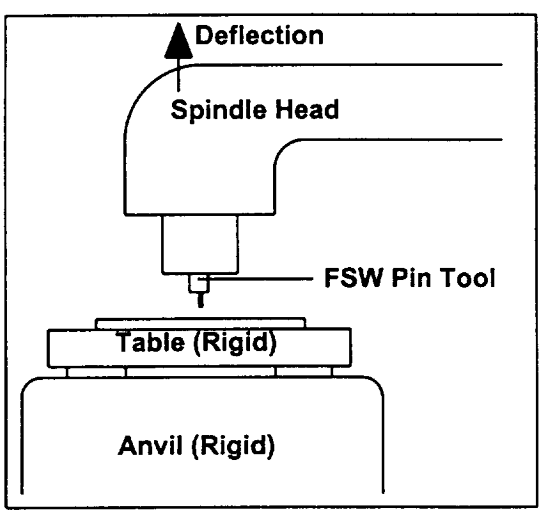

Figure 1 – Cincinnati milling machine setup. All deflection measured in spindle head. Anvil and moveable table have no measurable deflection.

Deflections of 0.004" were consistently measured along the pin tool axis. By simply adding this defection measurement to the desired plunge value, a reasonably accurate calculation could be made of the pin tool depth. Successful welds were consistently produced. However, the size of the milling table and its travel capability restricted panel size to 24 inches in length and 12 inches in width. In addition, only welds in the horizontal, flat position could be made.

Friction stir welding on the Niles gantry was another attempt at "scaling up" the process at Lockheed Martin Michoud Space Systems. A Lagun head was attached to the gantry structure with a stanchion as the backing anvil as shown in Figure 2. Both the head and the anvil deflected appreciably, but as stated above the welds were partial penetration. That application had no need to accurately control the penetration ligament within several thousandths of an inch. Therefore, welds were controlled by visual interpretation only.

The control system consisted of two parts. The Lagun head regulated rotation and plunge of the pin tool. These two parameters were controlled using CNC mode software installed on a personal computer. Travel was provided by the CNC based Niles tool post on which the Lagun head was mounted. A "countdown" procedure was used to synchronize the two control units manually due to the complexity of integrating the two CNC systems. Deflection measurements of 0.032" on the anvil and 0.020" on the head were recorded using this setup. Using the stanchion as a backing anvil limited overall weld length to approximately 8 inches. Despite the lack of any feedback control devices successful hybrid welds, including complex tapers on the ET STA 744 T-ring, were produced.

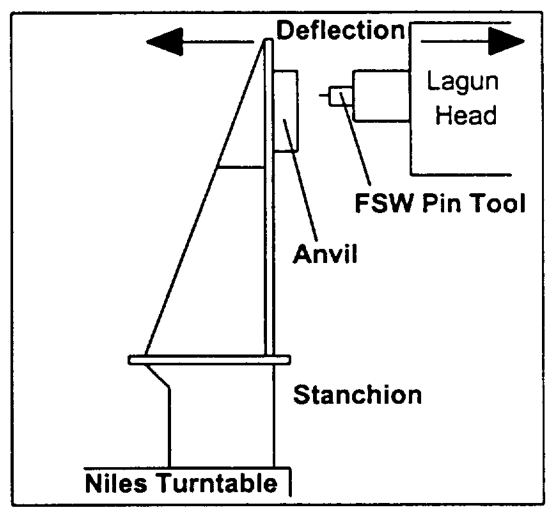

Figure 2 – Niles/stanchion setup. Deflection measured on both anvil and head.

Development of a larger, more rigid anvil for the Niles gantry provided the capability for longer friction stir welds. Welds of up to 36 inches in length were made with virtually no deflection using the anvil design shown in Figure 3a. Among the more interesting weld joints investigated with this setup was a simulation of a 2195 aircraft wing skin to a 2195 wing spar shown in Figure 3b. The experiment consisted of plunging the pin tool through a 0.165" panel (wing skin) partially into a 0.485" backing plate (wing spar). Again, plunge depth was controlled manually by the test engineer as the weld was produced.

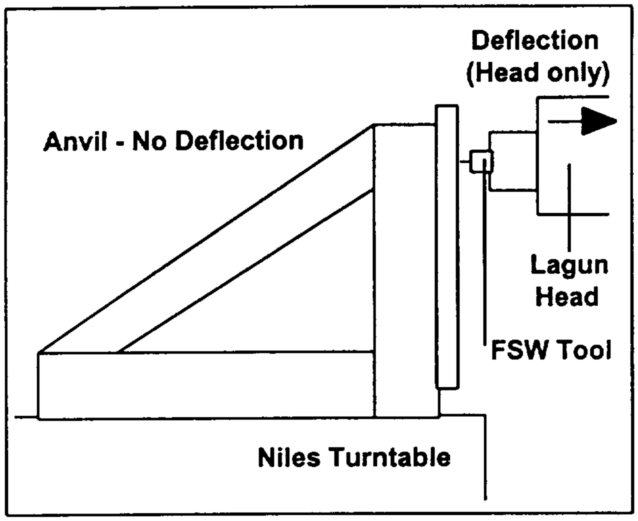

Figure 3a - Niles/beam anvil setup. No deflection measured on anvil.

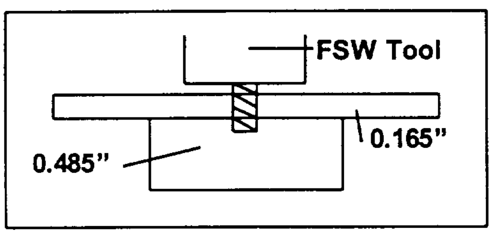

Figure 3b – Partial penetration lap joint simulating wing skin over wing spar.

The modification of the 15-foot Vertical Weld Tool at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama furnished a new perspective on tool design and the factors that govern weld nugget geometry. The weld head, built by Nicholson Manufacturing Company, Seattle, Washington, incorporates the use of two load cells. One load cell resides within the spindle assembly and measures plunge force, or forces normal to the panel surface. The other load cell measures forces along the direction of travel. Two axes (defined y and z *axes*) were built into the head, and the entire head assembly moves along the x *axis* as shown in Figure 4. The use of drive screws accommodates movement along all three axes.

The control system incorporates a Galil processor coupled with Visual Basic software installed on a personal computer. Input devices include the two load cells, a linear variable differential transducer (LVDT), and data acquisition capabilities. All weld parameters are recorded real-time as is thermocouple and strain gage data, when applicable. This information can then be transferred to an Excel spreadsheet for further analysis. Figure 5 illustrates the size of the 15-foot VWT as well as the stanchions required to support the final 27.5-foot diameter barrel section.

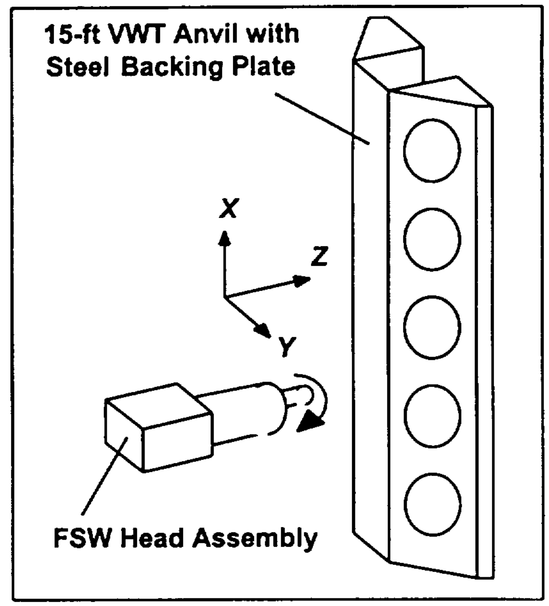

Figure 4 - 15-ft Vertical Weld Tool head and anvil setup. Plunge depth controlled along *z-axis*. Travel controlled along *x-axis*. Cross-slide controlled along *y-axis*.

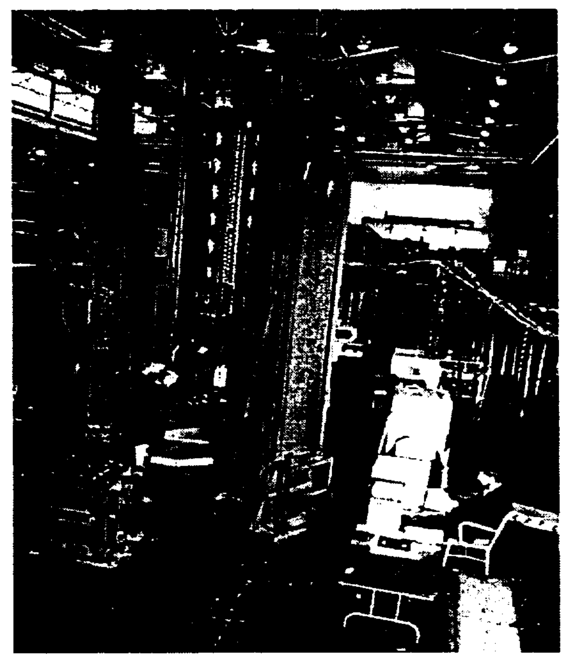

Figure 5 - Vertical Weld Tool setup including control cabinets and stanchion supports for full scale hardware demonstrations.

Loading Mechanisms - It was stated earlier that tool geometry and process parameters are the two mechanisms that determine the load within the system. General trends and correlations between variance of tool geometry and welding parameters can be made. Using two fixed tool geometries, comparisons were made of two shoulder diameters. All other aspects of the pin tool geometry were unchanged. It was shown that a 20 percent increase in shoulder diameter resulted in approximately a 50 percent increase in load for a given plunge depth. It was also observed that over the range of rotation speeds and travel speeds investigated, little effect on load was observed.

Loading during Welding - Shoulder plunge depth also played an important role in dictating the loading of the tool while making a weld. For a given tool it was demonstrated that a direct correlation between plunge depth and load could be made. This led to a philosophy of controlling the process using feedback from the spindle load cell instead of using a displacement transducer. Again, there is little effect on either load or plunge depth by varying tool rotation and travel speed while welding. However, tool rotation does have a dramatic effect on the load required to plunge the pin tool into the panel prior to welding.

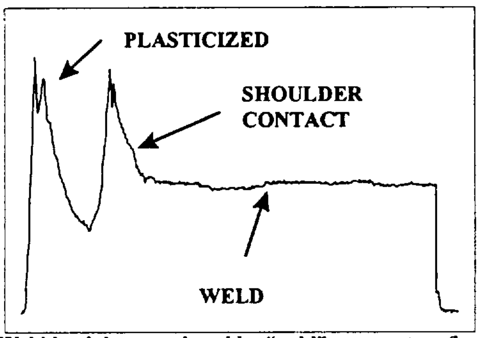

Figure 6a - Weld load data produced by "cold" parameters (ie. - slow tool rotation and fast travel speed). Note that the load spikes when the material plasticizes and when the shoulder contacts the panel.

Loading during Plunge - Figure 6a illustrates a load vs. time curve for a typical friction stir weld[4]. Notice that the load spikes when the tip of the tool begins to plasticize the material on the plunge. The other spike occurs when the shoulder contacts the surface of the panel. The severity of these spikes is dependent upon the tool rotation and the initial plunge rate. The amount of frictional heat that can be generated in a given time determines the magnitude of these load spikes. Figure 6b illustrates the effect of increasing the rotation speed. Both Figure 6a and Figure 6b were run with the same travel speed and penetration ligament (plunge depth). Only the tool rotation was varied in each case.

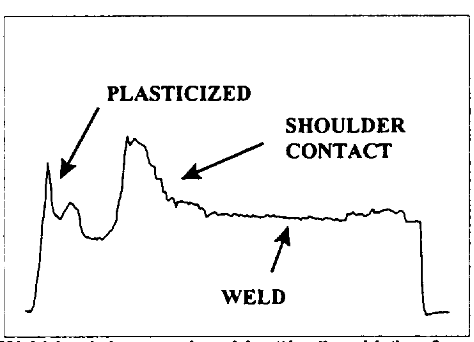

Figure 6b - Weld load data produced by "hot" weld (ie.- fast tool rotation and slow travel speed). Note the decrease in both the shoulder contact spike and especially the plasticized spike.

Since the maximum design load for the 15-foot Vertical Weld Tool was below these two spikes, considerable time has been spent trying to understand what can be done to minimize the magnitude of the load spikes. Through experimentation it was observed that tool rotation has the greatest effect on the plasticized spike while plunge rate has the greatest effect on the shoulder contact spike. The nominal load while running the weld is most dependent upon the depth that the shoulder of the pin tool is traveling below the surface of the panel. Figure 6c provides load data from welds being run presently.

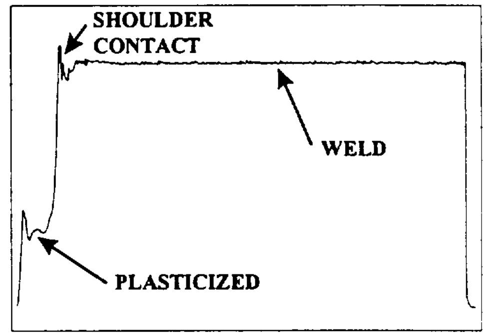

Figure 6c - Current weld load data from the most recent experiments using an optimum set of weld parameters procured from an orthogonal designed experiment.

The data collected thus far supports these principles *regardless* of the thickness of the material being welded. That is to say, for a given tool shoulder geometry and set of welding parameters, the load curves will be nearly equal even if pin length varies. This was demonstrated on 2195 material ranging in thickness from 0.320" to 0.650".

Mechanical Properties Comparison - Typical mechanical properties for friction stir welded 2195 panels are shown in Table 1. Better mechanical properties were obtained in some experiments, but at the expense of process robustness. It can be seen that friction stir welds of 2195 are stronger and more ductile than fusion welds at both cryogenic and room temperature. Also friction stir welds demonstrate less shrinkage and distortion due to less heat input and a lack of the severe microstructure changes associated with fusion welds.

Table 1 - Mechanical properties average for FSW and VPPA welds on 0.320" thickness 2195-T8 plate. Liquid hydrogen (-423 F) used as cryogenic medium.

	FSW - RT	FSW - Cryo	VPPA - RT	VPPA - Cryo
UTS, ksi	59	90-93	45	64
YS, ksi	37	61	N/A	N/A
%E (2"gage)	8-11	8-9	3	3

There was little or no effect from varying tool rotation, travel speed and penetration ligament in the range investigated. This shows that the process is tolerant of appreciable variations in any of the weld parameters. Nondestructive evaluations using radiography, fluorescent penetrant and ultrasonics confirmed the lack of welding defects associated with friction stir welding.

Summary and Conclusions

Tooling for friction stir welds can take many forms depending upon the philosophy used to control the process. Many have the opinion that massive, rigid machinery should be used to react the tremendous forces inherent to the process. This would eliminate, or at least minimize, deflection within the system. Control systems could take the form of very basic displacement measuring devices. Complexity of the process is decreased as is the skill needed to setup and run a successful weld. Controlling from a displacement perspective necessitates the use of stiff, rigid machinery.

On the other hand, if displacement is of secondary concern for controlling the process (ie.- load control) then accurate measurements of deflection within the system do not need to be made. Successful welds can be made by understanding how the forces involved with the process govern the outcome of the final weld. An understanding is then needed of how the forces, or applied load, is manipulated though tool geometry or weld parameters. Controlling from a load perspective has been demonstrated as being advantageous on tooling that lacks rigidity and lacks a flat, straight anvil. Both philosophies have advantages and disadvantages, and the best one shall vary according to the design of the tooling: rigid or flexible.

Acknowledgments

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