Space Shuttle ET Friction Stir Weld Machines

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Introduction

History

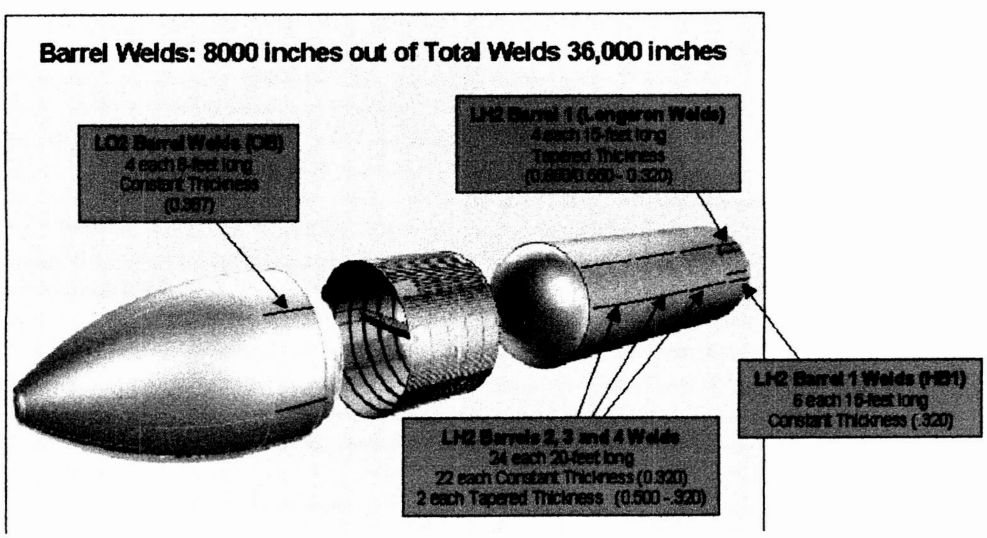
NASA and Lockheed-Martin approached the FSW machine vendor community with a specification for longitudinal barrel production FSW weld machines and a shorter travel process development machine in June of 2000. This specification was based on three years of FSW process development on the Space Shuttle External Tank alloys, AL2195-T8M4 and AL2219-T87. The primary motivations for changing the ET longitudinal welds from the existing Variable Polarity Plasma Arc plasma weld process included:

- Significantly reduced weld defect rates and related reduction in cycle time and uncertainty
- Many fewer process variables to control (5 vs. 17)
- Fewer manufacturing steps
- Lower residual stresses and distortion
- Improved weld strengths, particularly at cryogenic temperatures
- Fewer hazards to production personnel

General Tool was the successful bidder. The equipment is at this writing installed and welding flight hardware. This paper is a means of sharing with the rest of the FSW community the unique features developed to assure NASA/L-M of successful production welds.

Tank weld map

The ET is actually two tanks, LH_2 and LO_2, and is 27.5 feet (8.4m) in diameter. The cylindrical parts of the tanks are composed of curved panels, welded together into barrels. These panels are .320" to .650" (8.13 to 16.5mm) thick at the weld lands, and are typically machined to a thin membrane reinforced by waffle pattern ribs. As shown, a barrel is built up from as few as 4 panels to as many as ten panels, and are 8', 15' or 20' (2.4, 4.6, or 6m) long.



Tapered welds & locations

The ET is not just a tank, but also the unifying structure of the Shuttle system in the launch configuration, bearing loads from the Solid Rocket Boosters and the orbiter. At the attach points near the bottom of the tank, the tank wall is actually built of two heavily lugged, forged longeron panels that serve to spread the large out-of –plane local loads of the orbiter attachment fittings into membrane loads in the tank panels. To do this at acceptable weight, the panels are tapered in thickness, from as much as .650" to .320" (16.5 to 8.13 mm) over the length of the 15' (4.6 m) Barrel 1. This tapered weld was a significant driver to the process development program, and led NASA/L-M to do pioneering development in retractable pin/probe FSW welding. In addition to geometric challenges, the forged panel is a different alloy than the adjoining tank panels. This leads to another significant variable in process development, as well as the possibility that the weld spindle might have to rotate both ways.

The tapered welds of the longeron panels and the large lugs and ribs on the panels are significant drivers of the FSW machine design. They require RPT features in the weld head, constrain the geometry of the weld anvil, and constrain the shape of the panel clamp nosepieces. The lugs extend radially outward from the skin surface of the tank, and lead to the need to retract the anvil away from the tank to rotate the tank assembly in the machine.

Machine Specifications

Clamp loads, geometry & access to weld seam for inspection

L-M specified 300 lbs/inch (53 N/mm) of clamp force. This is not enough clamp force to weld the panels in a single pass. Precedent equipment in the FSW process development had this force limitation, and NASA/L-M concluded that a "tack pass" with a very short, .050" (1.3 mm) pin tool was a given. When 600 lb./in, (106 N/mm) from two rows of clamps, is applied over the 20.5' (6.2 m) long panels, it results in a very large distributed force on the machine structure, 162,000 lbs. (721 kN).

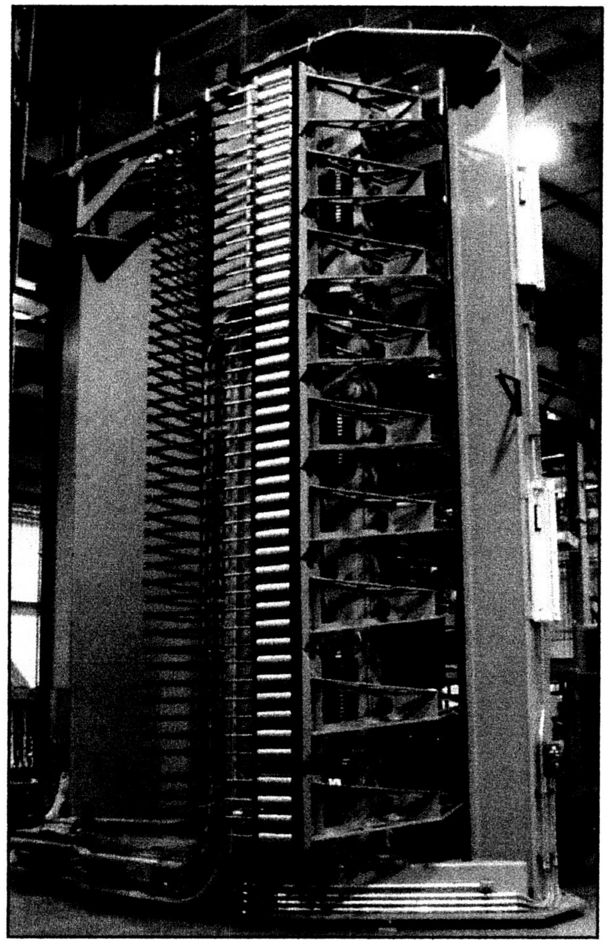
The specification required access to the weld joint at any point in the process by an inspector or weld engineer for checking fitup or inspecting the welds. This requirement, in addition to a requirement to clear any of the workpiece hardware by 3" (76 mm) including the longeron panels with its ribs, led us to a rather long clamp arm. The alternative, which we did not want to consider, was to have the clamp column and the weld column move to gain this clearance. This choice would have resulted in a machine design in which all machine structures moved to index panels. Another set of requirements on the clamp system were pneumatic actuation, the ability to clamp either tapered or flat panels and corrosion resistant clamp surfaces that would not scratch or mark the surface of the flight hardware. Finally, the clamps were to clamp perpendicular to the surface of the work, neither closing nor opening the joint. This requirement led to a mechanism that, at contact with the work, has an instant center of rotation on the other side of the tank panel, or is a straight line motion mechanism.

Seam tracking – inspection

A seam tracking system was specified, along with +/- 1" (25 mm) of active cross-weld motion. This axis also needed a loadcell to measure cross-axis welding forces.

Overall Machine Design

Machine Concept



The machine was designed as a set of four independent vertical beams. While they look like columns, the machine elements are all vertical beams with lateral loads applied by the FSW process and clamping.

The largest of these is the anvil. The anvil translates radially away from the panels about 14" (36 cm) to achieve a minimum part clearance of 3" (76 mm) from the longeron lug that extends approximately 11" (7.6 cm) out from the ET skin. When the machine is in a welding configuration, 2 substantial air –actuated shot pins lock the anvil to the base of the machine. At the top, four additional shot pins connect two triangular link arms between the anvil and the top of the machine to constrain the anvil to the rest of the machine in all translational degrees of freedom. When the lock pins are withdrawn, the link arms can be moved out of engagement and the anvil is moved on linear ways by an acme screw jack, ac motor and limit switches. When the anvil is commanded back to the weld position, the bottom two pins engage automatically, and the top arms are moved and pins engaged manually. Proximity switches assure that the machine is completely pinned together before the controls will proceed with the weld process.

One structure carries the weld head guiding ways and one set of clamps. It is a plate weldment. There is an adjacent structure, built of steel tubing, which carries the other set of clamps.

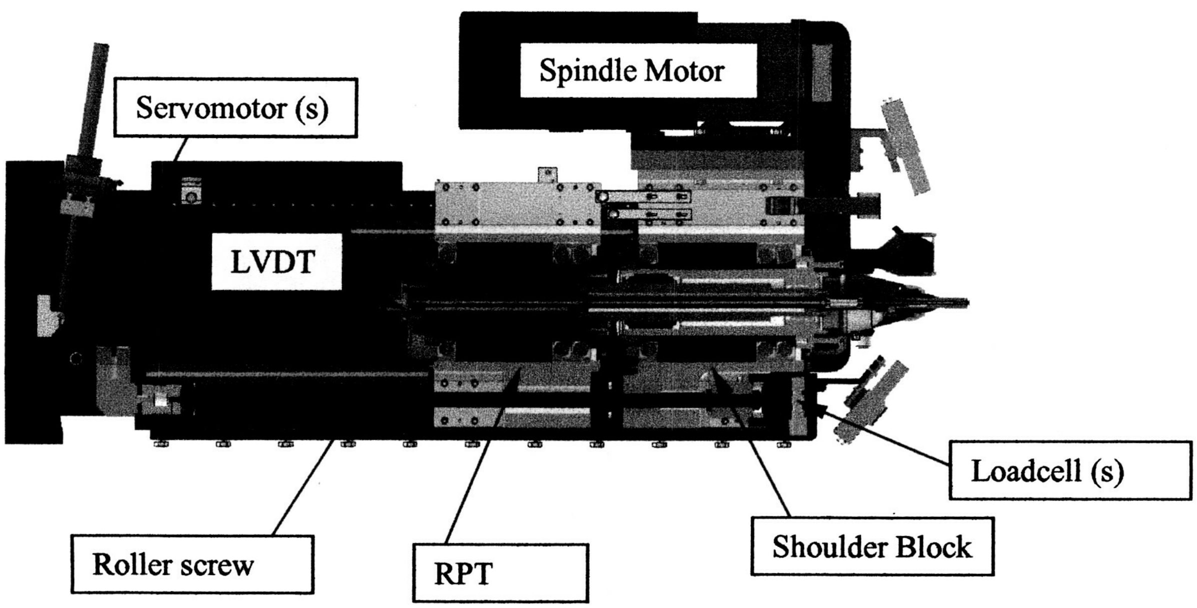
The fourth vertical beam is the force balance beam, and it, by the design of the machine mechanisms, carries the clamp forces imposed on the work and anvil and the process plunge forces, possibly in excess of 20,000 lbs. (88 kN).

The panels to be joined into barrels are suspended from dedicated shoes that engage tooling holes in the panels. The panels are lifted into position hanging vertically from an overhead crane. They are then attached to a system of adjustable trolleys. The trolleys support the panel and give the machine and operators the ability to adjust the alignment of the panel in all degrees of freedom to bring its edge to be welded into alignment with the center of the anvil (or the faying panel). The trolleys roll freely around a circular track to index the barrel and panels through the process of completing all of the welds in the barrel. The circular support rail and panel hangar system are supported on dedicated columns to the floor independent of the FSW machine structure.

The requirement of making the weld accessible to weld engineers or inspectors was satisfied by attaching a personnel platform to the top of the weld head and using the head as an elevator to take the person requiring access to the proper location. In addition, the machine is surrounded by an extensive platform system to provide access to the workpiece in process.

RPT Head design

The shoulder and RPT pin both have requirements for precise positioning and large forces. We concluded that these challenges were best met by having coaxial, independent bearing systems for the shoulder and retractable pin. The retractable pin is attached to large a ballspline bar that reaches through the hollow shoulder spindle. The shoulder spindle is driven by a variable speed AC motor driving through a 3:1 gearbox and a herringbone toothed belt. The retractable pin is driven in rotation by the ballspline attached to the shoulder spindle. In normal operation, the retractable pin axis moves relative to the shoulder axis by only 1" (25.4mm). The RPT spindle is typically slaved electronically to move with the shoulder. During a retractable pin weld, this kinematic arrangement results in the pin essentially plunging and remaining a fixed distance off of the anvil, and the shoulder then moves as required to follow the surface of the panels. During fixed pin welds, the RPT plunge axis is simply servo gearlocked to move with the shoulder. The spindle systems can be jogged independently to several inches of separation for maintenance access to the machine.

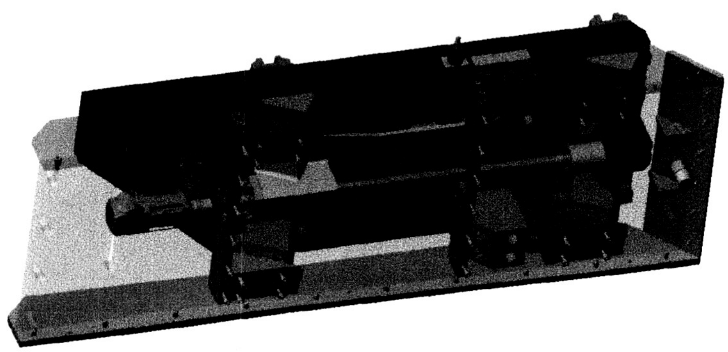


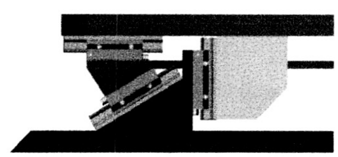
Actuation/load measurement

The shoulder plunge, RPT plunge and cross axes are each actuated by a brushless servomotor, gearbox and roller screw system, and the thrust reaction point for the screw is attached to a loadcell. The vertical travel axis is driven by a ballscrew, with a loadcell located between the ballnut and the carriage. The ballscrew is driven by a brushless servomotor, worm gearbox and bevel gearbox. The worm gearbox was used on this to axis prevent the head from descending under its own weight in case of brake failure. In addition, the vertical axis is equipped with a linear brake device that will only let the head descend while all control system parameters are correct and a descend command is present.

Each motion axis is equipped with a rotary encoder on the motor shaft for commutation and stability, and a linear encoder independent of the axis drive that measures absolute motion. This encoder removes concerns of screw system compliance and loadcell compliance from position measurement.

A unique wedge way system was employed to provide the +/-1" (25 mm) motion in the cross axis direction. A plate with four wedges moves on linear ways, and the slide is attached via linear ways to the other side of the wedge. Another pair of linear ways keeps the distal and proximal halves of this mechanism aligned in the direction of the wedge motion. The distal part is then forced to move by the tangent of the wedge angle when the wedges are displaced by the roller screw. Force in the cross axis direction is measured successfully at the roller screw reaction, with a slightly larger friction band than the other axes.





Force-Balance Concept [1]

Parallel structure

The force balance beam, mentioned earlier, is a redundant loadpath from the clamp system or the head to ground. The force balance beam was added to the structure to carry the large forces. The weld column, which guides the head and is therefore a measuring coordinate system, provides dynamic stiffness, but doesn't have to carry large static loads and thereby exhibit static deflections.

This idea was mechanized in the case of the clamps with a passive system, and in the case of the process load, it was mechanized by an active system.

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[1] Patent Pending

Anvil description

The anvil is a 38,000 lb. triangular beam. It is connected to the top of the machine in a pinned (in the structural sense: the connection does not carry bending moment) connection. The bottom of the anvil is also a pinned connection, and the way system that the anvil moves on was designed to be compliant to minimize the moment carried when the anvil carries bending loads. The face of the anvil is a set of identical [redacted] wear bars. → Stainless Steel

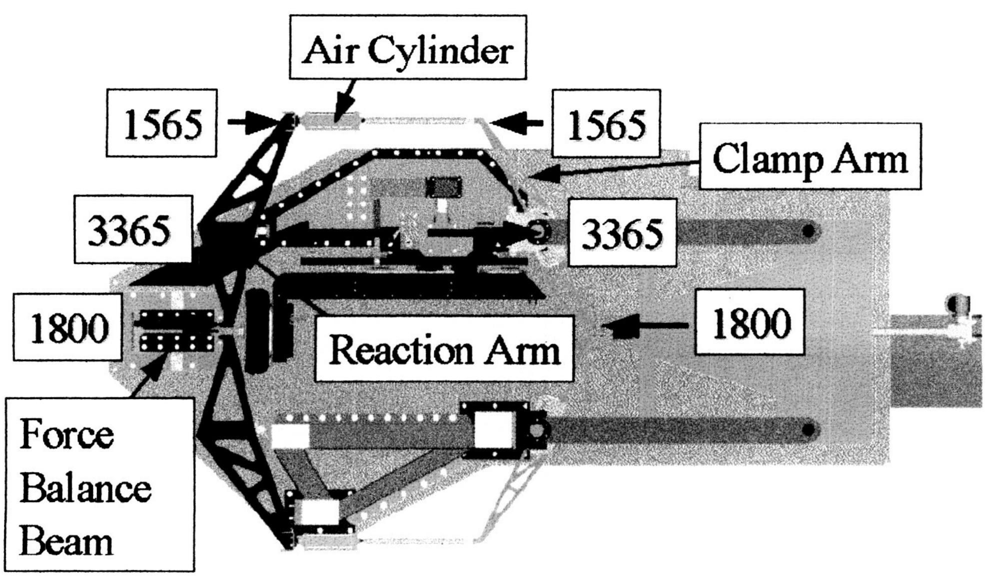
The pinned-pinned end condition was used because it is the end condition that will be the most consistent over the life of the machine and over numerous connect-disconnect cycles. The anvil surface was mapped by using the machine linear sensors to measure plunge displacements at nominal clamp and process loads. The error map is then used to obtain the most accurate positioning of the tools to the anvil, and compensates for straightness errors in the weld column ways, the anvil and the anvil deflections.

Force Balance Implementation

Clamping Forces

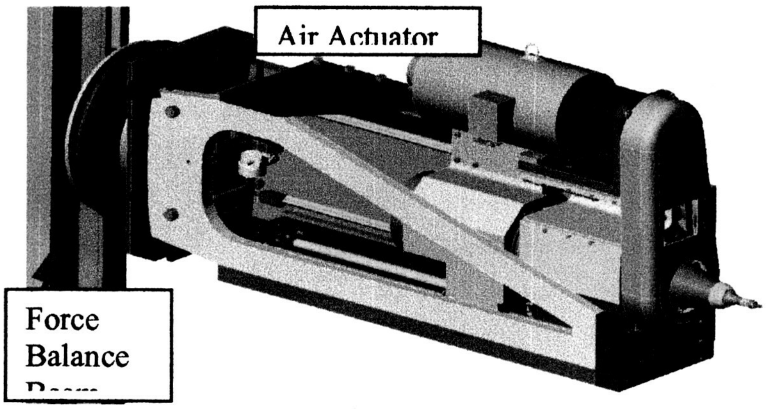
The clamp cylinders are attached between two geometrically identical levers. The reaction forces at the pivot points of these levers are equal and opposite. The attach point for the reaction levers (there are actually five clamp levers to a reaction lever) is attached to a compression member that carries the clamp load at the back to the face of the weld column. This eliminates any compression of the weld column that would tend to reduce the distance between the head guide ways. As the force balance beam deflects, the air cylinders simply contract a bit more while maintaining the desired clamp force. The structure that guides the head and is used as a measurement frame of reference is in this manner freed of any net force from the clamping mechanism. The same system is used on the other side of the machine as well.

The pneumatic system is single fault tolerant. Once the clamps are all set, the failure of any hose connection or single valve will not change the clamping forces.



Process plunge force

Loadcells measure the RPT force and the shoulder force. The control system sums those forces, and commands a proportional air pressure by means of an electronic air pressure regulator. This air pressure is applied to a large rolling diaphragm air actuator, interposed between the head of the machine and a linear guideway on the face of the force balance beam. This active system creates an equal and opposite force to balance the plunge forces on the pin and shoulder, and the tool plunge forces are thereby applied to the force balance beam rather than the weld column. When static deflections are measured at the tool relative to the machine coordinate system, the machine stiffness is from 10-20 million pounds/inch.



Top and bottom beam ties

The force balance beam exhibits a fair amount of deflection, on the order of .20"(5 mm). The top of the force balance beam is rigidly connected to the unifying top plate, which flexes with the beam. The top plate connects the clamp column, weld column and force balance beam. The bottom of the force balance beam bears on pin in the center (thickness) of the base plate of the machine. Since the base plate is grouted to the floor, flexing of the base plate out of plane is undesirable.

Spindle design incorporating RPT growth measurement[2]

Description of thermal growth issue

As the pin is plunged into the work, process heat diffuses up the pin. As the pin heats up, it grows longer. The positioning of the pin relative to the anvil is the most critical position control issue in the machine. The magnitude of the thermal growth is .025-.030". At the same time, the compressive load on the pin shortens the pin by about .010". The actual instantaneous thermal growth and compression shrinkage depend on a number of conditions. To meet the specification, we developed a means to directly measure the changes in pin length continuously, throughout the weld process.

Measurement of the pin length directly, in process, simplifies a number of other concerns. Pin compliance and heat wicking up into the machine is simply not a problem with this system in place.

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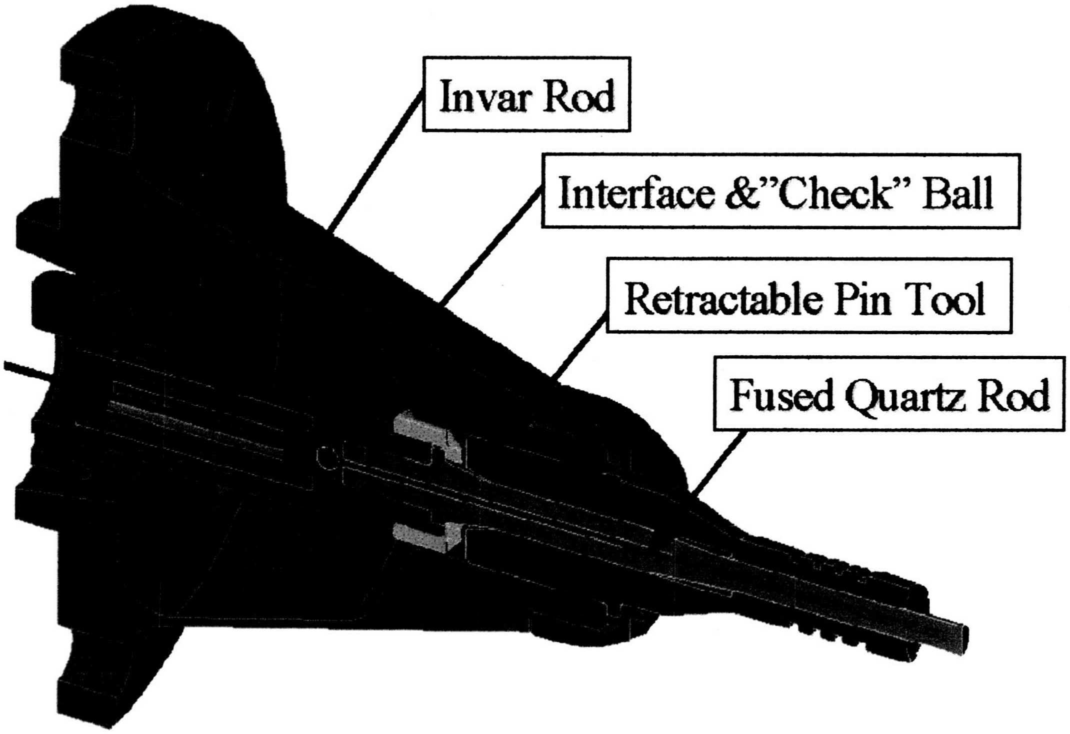
[2] Patent Pending

Sensing rod concept

The length of the pin is measured in process by means of a 3mm diameter fused quartz rod. Fused quartz exhibits a very low coefficient of thermal expansion, about 3.00E-07 in/in/°F. This value is about 3.6% of the [redacted] pin, which exhibits a CTE of about 8.29E-06 in/in/°F. These values are approximate because both materials have non-linear thermal expansion in this temperature range. Using a very low CTE pin makes the measurement system essentially immune to thermal effects, and lets a single system measure thermal growth, mechanical compliance and any backlash.



Thermal growth system implementation

The pin is drilled by a combination of deep hole and EDM methods to very near the end. A .125" alumina ball is placed in the hole to provide a stable interface to the flat ended fused quartz rod. The rod is bonded to a brass tube where it exits the removable pin holder to protect it from side loads. A silicone o-ring holds the rod in place so that it won't fall out of the tool. The fused quartz rod bears on another ceramic ball retained in the pin tool chuck in the RPT spindle. The ceramic ball bears on an Invar rod that transmits the motion of the fused quartz measuring rod to the back of the RPT spindle. A hardened steel spring-loading cap that preloads the measuring rod stack.

All of the sensing rods rotate with the spindle. A stationary, spring-loaded LVDT with a carbide ball tip is attached to the RPT spindle block. The LVDT plunger carbide ball bears on the center of the rotating cap, and measures the net motion of the spindle and measuring rods relative to the block. The block position is measured directly to the carriage by the RPT plunge linear encoder.

Results

The mechanical compression and subsequent thermal growth of the pin can be seen very clearly in the LVDT measurement during the plunge of the RPT and traverse up the weld. The system accurately measures pin end position to .0001" (2.5μm) insensitive to temperature or compression strain.

Control System

Basic architecture

The four motion axes are controlled at the servo level by a Galil motion control board. The Galil board also runs a process control loop that integrates force measurements and the pin growth measurement into the displacement control. There is also a PLC that handles machine I/O, controls anvil motion, clamps, interlocks and communication with the plant network.

Controlled variables and limited variables

The shoulder plunge and RPT axes can each be controlled on load or position basis. To make the control safer and the process more robust, when one of these parameters is selected as the primary variable, the other is subject to trim, alarm and termination limits prescribed in the weld schedule. Any combination of choices for primary variable is supported.

Weld schedule

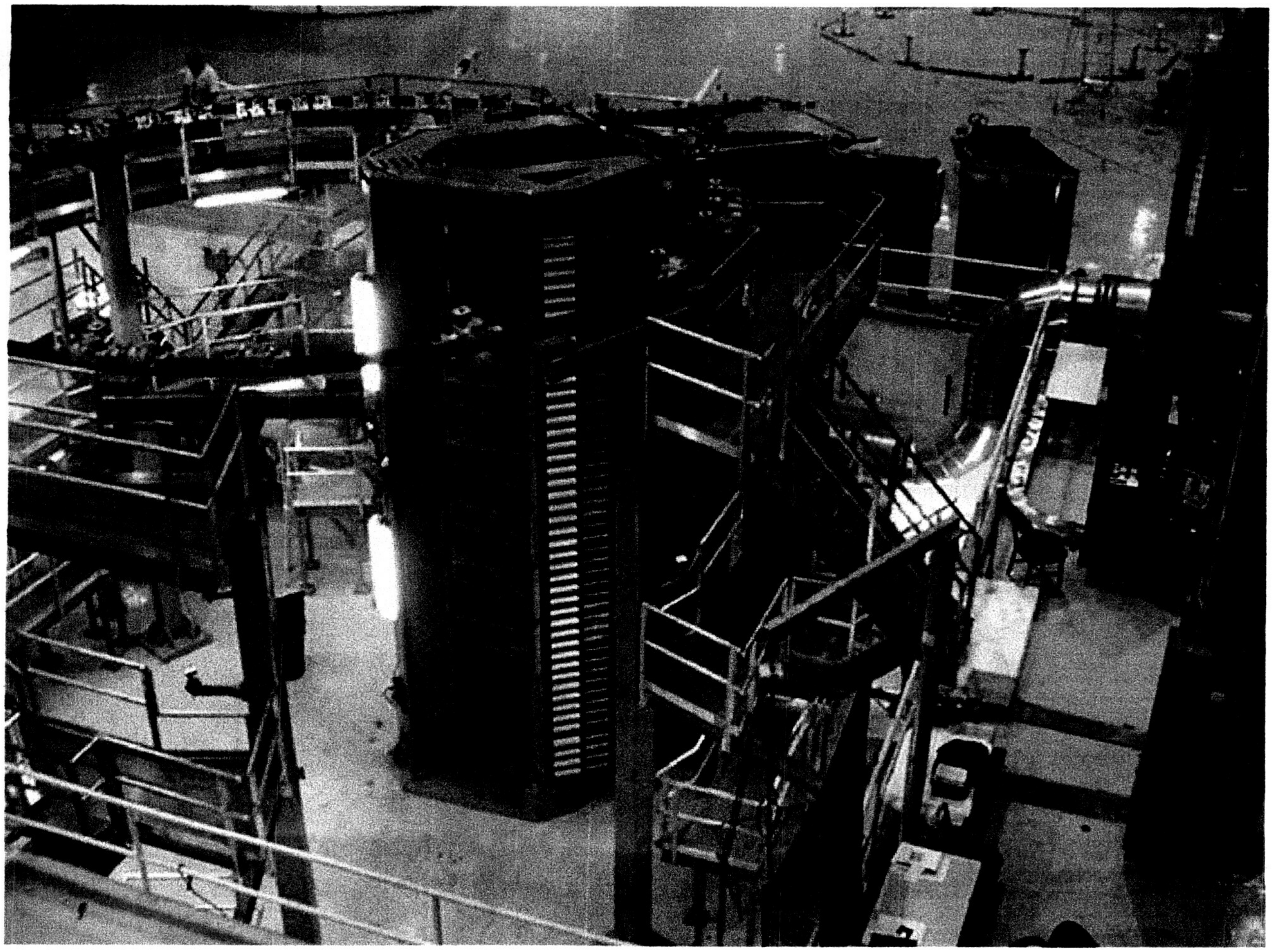
Specification of the weld parameters and desired setpoints is made for a particular weld in a "weld schedule". The schedule, built in Excel, is very similar in structure and approach to the weld schedule approach that has been used to control fusion welding on the ET. Welds are broken up into segments by linear position along the weld, and variables can be ramped from a starting value to a finishing value in a linear ramp over a specified linear travel. Schedules are tied to particular part number combinations and are protected by a multi-level security system

Weld tracking and seam scan

The specification called for a joint tracking system to guide the head along the weld, as well as a height sensor system that was originally used to compensate for machine compliance.
As the system was designed and developed, the project team decided that these sensors were actually more appropriately used to automatically inspect the faying condition of the panels for acceptable gap, actual panel thickness (surface height relative to anvil height) and desired weld trajectory in the cross weld direction. Use of the sensors prior to the welding process in a seam scan allows the system to check for acceptable panel thickness and setup, correspondence of loaded parts to weld schedule selected. The measured panel thickness is combined with joint position and the anvil map to generate the tool path for the weld. The operator examines a display of seam scan measurements and adds judgement and experience to hard go-no go limits on the measured values before initiating a weld program. These seam scan measured values are retained as production process metrics. During the weld, the operator may make limited trim inputs to all important weld schedule parameters

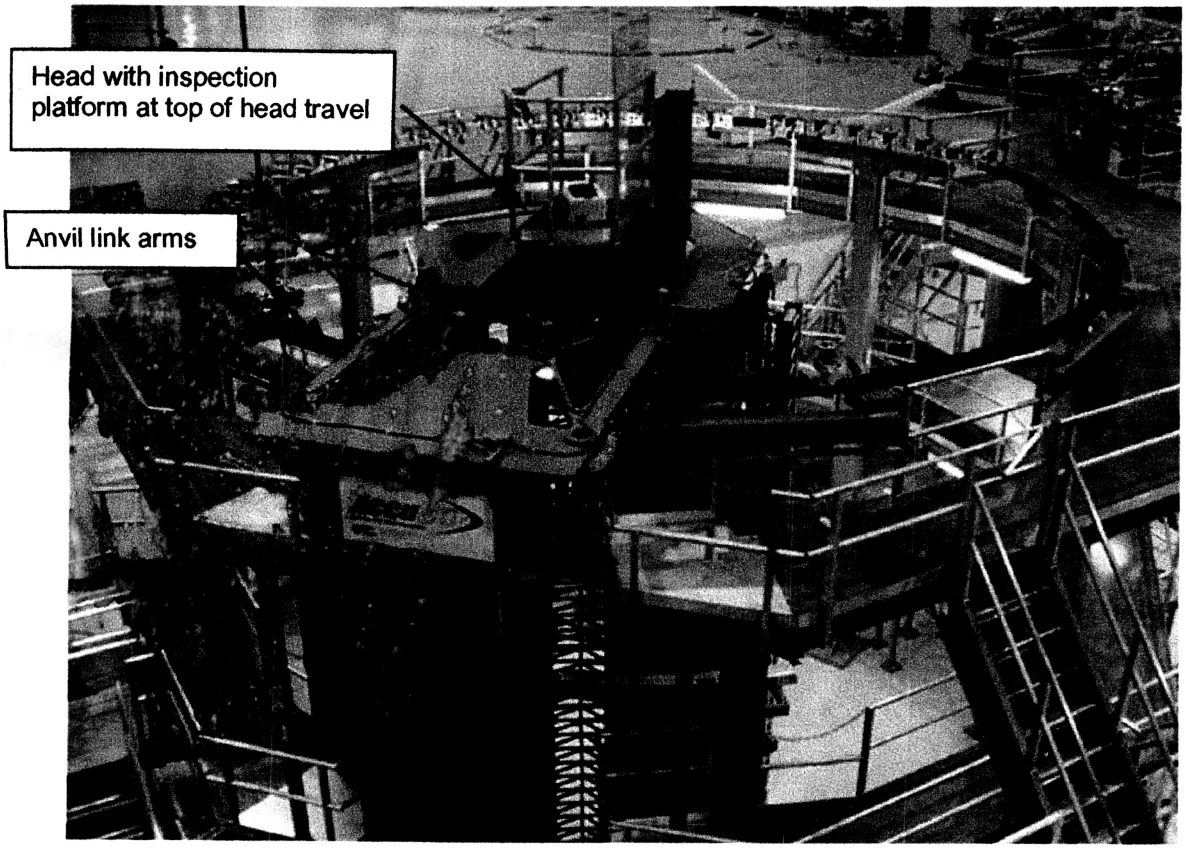
Data Logging

The control system includes a flexible and elaborate system for recording and displaying weld parameters as a function of time and position in the weld. There are a number of special features to support datalogging and storage to successfully endure a number of possible single point failures of various system components, (such as hard drives) and interruptions in power supply. The logged parameters are stored electronically and can be printed out continuously during the weld. The logged process parameters for each weld are filed and retained for quality control purposes.



Conclusion

The first flight-qualified hardware was welded at the close of 2002. The FSW program originally called for an additional machine to be used to either weld the opposite side (root) of each weld or to be available to perform repair passes as required. Part way through the design and review process for these machines, NASA was sufficiently confident that this equipment would produce sound welds from one side that the additional weld station was eliminated. Implementation of the FSW process into ET production is a successful Shuttle Upgrade Program. This technology and equipment will make the shuttle program safer and more affordable. FSW of the Space Shuttle ET will be one of the most visible and publicized applications of the process, and General Tool is proud to have been a part of it.


Head with inspection platform at top of head travel
Anvil link arms