SAND2017-2939C

# Failure of Laser Welded Structures Subjected to Multiaxial Loading: Experimental Development

Bonnie R. Antoun, Kevin Connelly
Sandia National Laboratories, Livermore, CA 94551

## ABSTRACT

A unique experimental capability was developed so combined mechanical and thermal loads could be imposed on specimens that are representative of laser welded structures. The apparatus, instrumentation and specimens were designed concurrently to yield the ability to apply a wide range of loading conditions that accurately replicate the multiaxial stress states produced in laser welded, sealed structures during pressurization at high temperatures up to 800 C. Axial, radial and torsional loads can be applied individually or in combination, by direct or variable loading paths, to eventual failure of laser weld specimens. Several advantages exist for applying equivalent stress states by mechanical means rather than pressurization with gas, including: repeatability, controlled failure, safe experiments, assessment of loading path dependence, experimental efficiency and overall facility. The experimental design and development are described along with resulting measurements and findings from sample experiments.

Keywords: laser weld, stainless steel, failure, multiaxial loading, elevated temperature

## BACKGROUND

Laser welds are used to join materials while imparting minimal heat beyond the local weld region, preventing both unwanted container distortion and damage to nearby parts or components. In this study, of particular interest are partial penetration laser welds used to seal stainless steel containers that encase organic materials such as potting foams. These containers can be exposed to elevated temperatures that degrade or decompose the internal materials which pressurizes the container, leading to possible failure of the container walls or the laser weld, depending on geometry, material and weld properties. Prior work was focused on container wall failure [1-3] with coupled thermal-mechanical experiments that applied pressurization with nitrogen gas during asymmetric heating and later focused on laser weld failure under uniaxial, isothermal loading [4]. The current work progresses to mechanical application of pressurization stresses in laser welded structures.

## MATERIAL

The material used in this study was a 4 inch (101.6 mm) diameter bar of 304L VAR stainless steel, produced by Electralloy. The chemical composition is shown in Table 1 and the average grain size was ASTM 5 with the largest grain size in the material equal to ASTM 4 (100 μm). Some of the mechanical characterization results are shown in Figure 1 [5].

## SPECIMEN DESIGN

The specimens were made from the 304L VAR material described in the previous section and are shown in Figure 2. Each specimen consists of two parts: an inner stud that has an internal thread for coupling to the test fixtures and an outer disk of radial type or torsion type. The specific geometry details of each part can be tailored to match the structure geometry being studied and several variations of these specimens have been prepared. Figure 3 shows a weld fixture that was designed and used for repeatable alignment when the two (inner and outer) parts of each specimen were laser welded together. Typically, laser weld penetration depths of about 0.75 mm (0.03 inches) for fifty percent weld penetration were produced. Figure 4 shows an example of a completed laser welded specimen.

The radial loading specimen was designed with an outer lip that is used to apply an outward radial load on the specimen and the torsional loading specimen was designed with an outer hexagon shape, used to apply a torsional or shear loading on the specimen by coupling with the fixtures described in the next section.

**Table 1** Chemical Composition (wt %) of 304L VAR stainless steel material

| | | | | |
|---|---|---|---|---|
| **Al** | **B** | **C** | **Co** | **Cr** |
| 0.009 | 0.0014 | 0.022 | 0.055 | 19.02 |
| **Cu** | **Fe** | **Mn** | **Mo** | **N** |
| 0.092 | Balance | 1.38 | 0.16 | 0.02 |
| **Ni** | **O** | **P** | **S** | **W** |
| 10.14 | 0.003 | 0.020 | 0.002 | 0.017 |
| **Si** | **Ti** | **V** | **Nb** | **Sn** |
| 0.63 | 0.0036 | 0.049 | 0.019 | 0.012 |

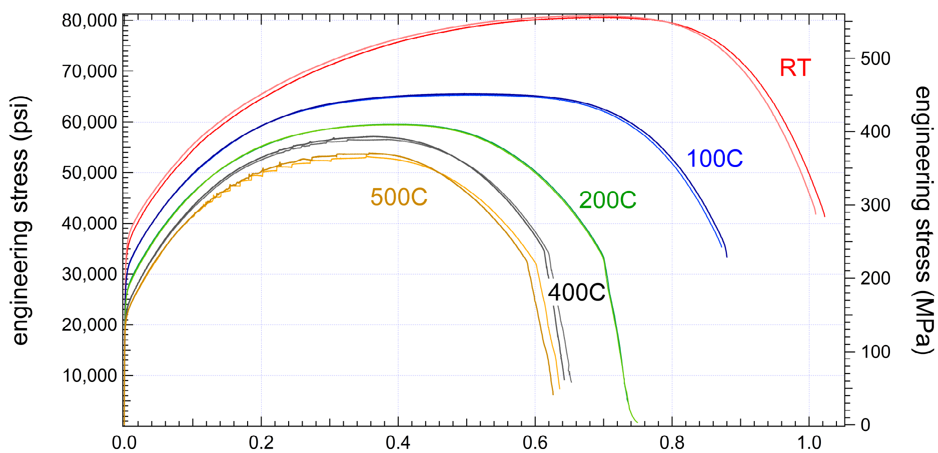


**Fig. 1** Tensile behavior of 304L VAR stainless steel, note dynamic strain aging is evident at 400C and 500C [5].

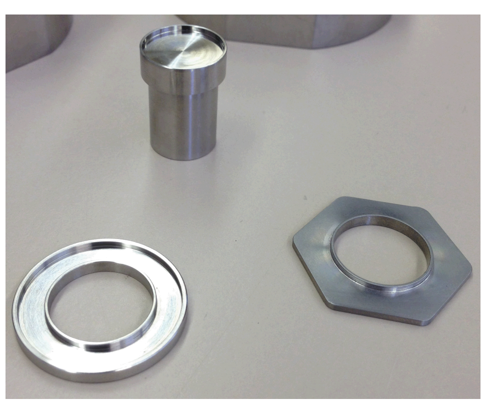

**Fig. 2** Laser weld specimen parts: inner threaded stud (top) and outer radial disk (left) or outer torsion disk (right).

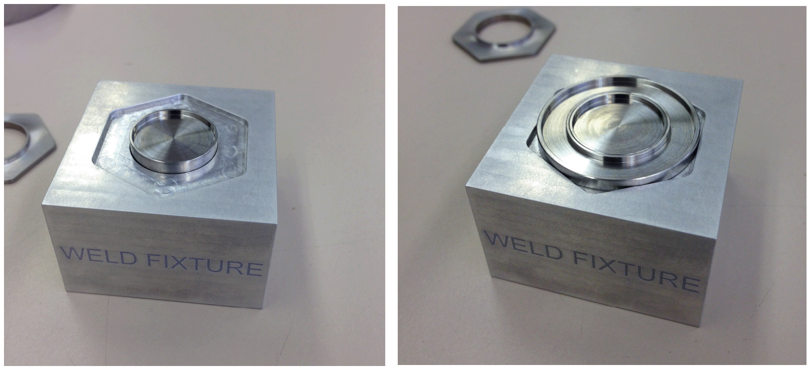


**Fig. 3** Fixture for precision aligning specimen parts during laser welding: inner threaded stud placed (left) with outer radial disk (right).

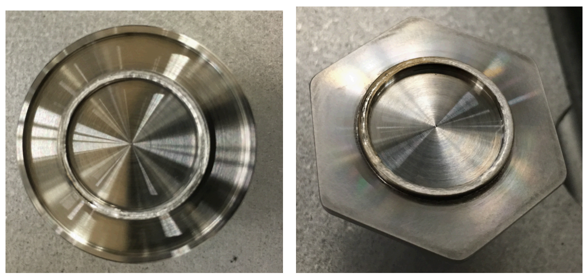

**Fig. 4** Radial loading (left) and torsional loading (right) specimens after laser welding inner and outer parts.


**Fig. 5** MTS Bionix axial-torsional test frame used for laser welded specimen experiments.

## EXPERIMENTAL DESIGN

The fixtures and instrumentation were designed to operate on an MTS Bionix axial-torsional test frame shown in Figure 5. The fixtures consist of a threaded rod that applies axial tensile or compressive loading through the inner threaded part of the specimen. The fixtures that sit above and outside of the specimen apply either radial or torsional loading by attaching to the outer part of the specimen. A schematic cross-section is shown in Figure 6 for the radial loaded specimen. Additionally, a camera mount fixture is incorporated in the upper fixture to allow for continuous viewing of the entire top surface of the laser weld throughout each experiment. Figure 7 shows a photograph of a radial loaded laser weld specimen being installed in the test fixtures. Four 4.4 kN (1000 lb) load cells are used to monitor the radially applied load on the specimen during testing. A type K thermocouple is spot welded to the inner wall of the laser welded structure to monitor temperature.

All fixtures were constructed of Inconel for high temperature performance. Heat is supplied to the specimens by a custom designed coil and induction heating system that heats the threaded rod directly below the specimen, as illustrated in Figure 8. A live optical camera image enables observation and recording of laser weld deformation and failure throughout experiments. All measurements and signals are recorded through the MTS test frame software.

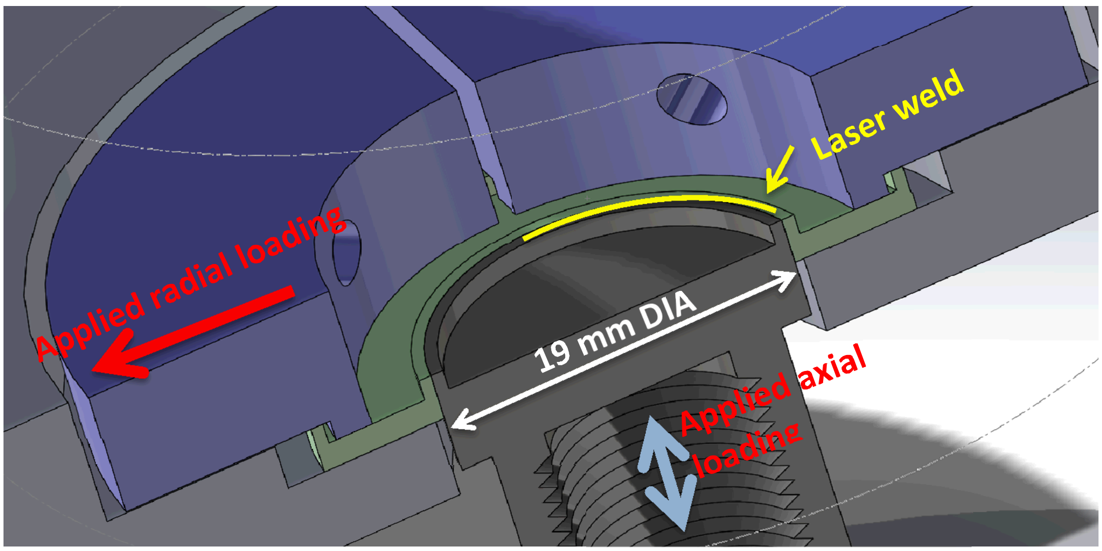


**Fig. 6** Schematic cross-section showing radial loading using outer lip of specimen and fixtures.

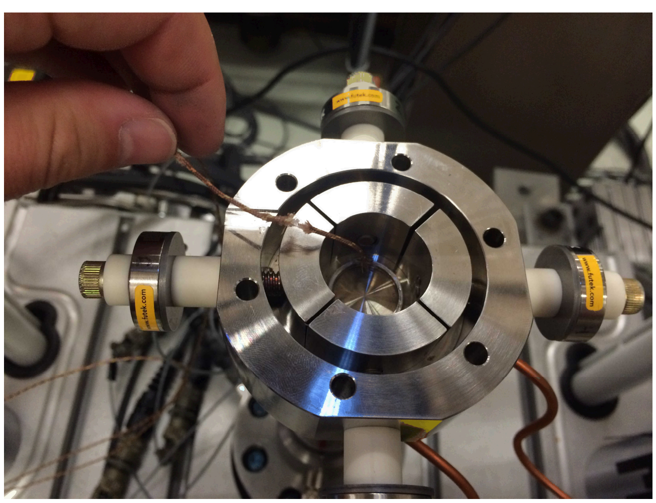

**Fig. 7** Photograph showing radially loaded laser weld specimen mounted in fixtures.

**Fig. 8** Photograph showing induction heating of threaded rod and specimen.

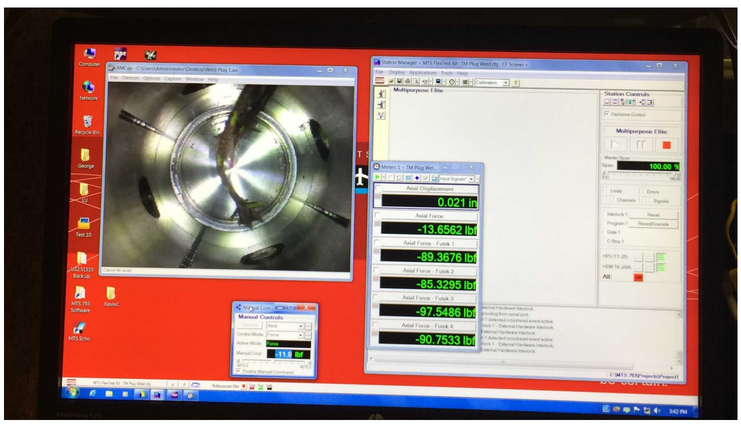


**Fig. 9** Live optical (camera) image to observe laser weld deformation and failure.

## INITIAL RESULTS

Several successful experiments have been completed using the new capability. A sample result is shown in Figure 10 as an example. This experiment illustrates a moderately loaded specimen tested at 400 C and subjected to radial loading followed by axial compression loading until failure. A photograph of the specimen after failure is shown compared to an untested specimen in Figure 11.

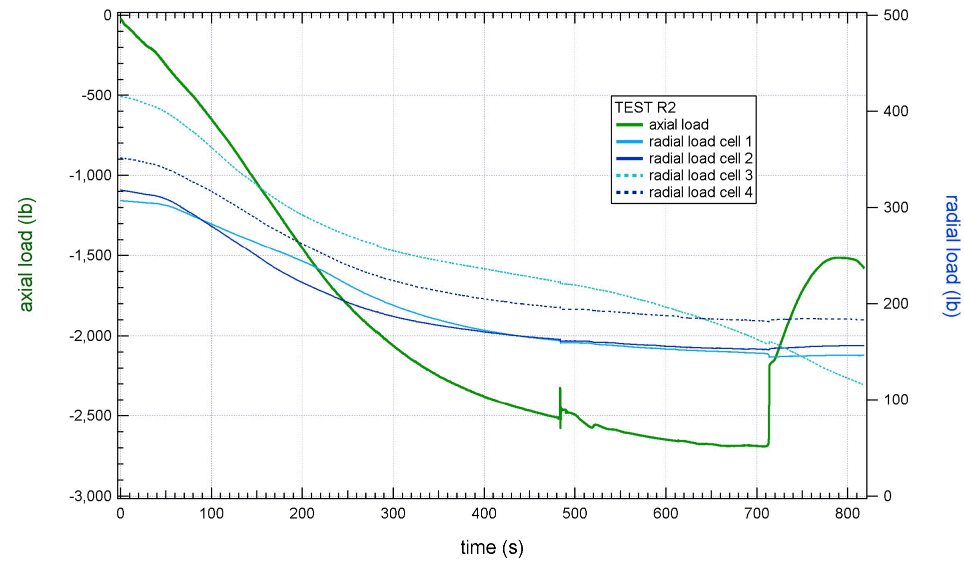


**Fig. 10** Example experiment at 400C with combined radial and axial loading of the laser weld specimen to failure.

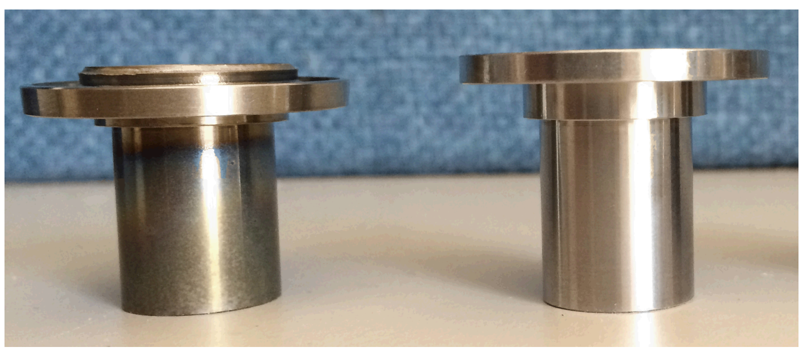

**Fig. 11** Photograph of specimen after testing to failure (left) compared to a specimen before testing (right).

## SUMMARY

An experimental capability for testing laser welded specimens under pressurization type loading or resulting stress states at elevated temperatures has been successfully designed, implemented and proven. The specimen design coupled with the fixture designs provide great flexibility in studying all pertinent variables including geometry and laser weld details and features, applied temperature, stress state and applied stress path. Additional experiments are being conducted, fully utilizing the design features and functions of the capability.

## ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

**REFERENCES**


1. Antoun, B.R., Dempsey, J.F., Wellman, G.W., Scherzinger, W.M. and Connelly, K., "Design and Implementation of Coupled Thermomechanical Failure Experiments," *Proceedings of the 2010 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, Indianapolis, Indiana, June 7-10, 2010.
2. Antoun, B.R., Dempsey, J.F., Wellman, G.W., Scherzinger, W.M., Connelly, K., and Romero, V.J., "Coupled Thermal-Mechanical Experiments for Validation of Pressurized High Temperature Systems," *Proceedings of the 2010 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, Indianapolis, Indiana, June 7-10, 2010.
3. Antoun, B.R., Dempsey, J.F., and Wellman, G.W., "Experiments and Predictions of Large Deformation and Failure in Thermomechanical Loading Environments," *Proceedings of the 2011 SEM Annual Conference & Exposition on Experimental and Applied Mechanics*, Uncasville, CT, June 13-16, 2011,
4. Antoun, B.R., Connelly, K., "Effect of Applied Temperature and Strain Rate on Laser Welded Stainless Steel Structures," *Proceedings of the 2015 SEM Annual Conference on Experimental and Applied Mechanics*, Costa Mesa, CA, June 8-11, 2015.
5. Chambers, R.S., Emery, J.M., Tandon, R., Antoun, B.R., Stavig, M.E. and Newton, C., "Characterization & Modeling of Materials in Glass-To-Metal Seals: Part I," SAND14-0192, Sandia National Laboratories, January 2014.