SAND2023-01174R

Term Project: Laser Welded Burst Disk Weld Tooling

MAE 259: Modern Manufacturing Technologies

Matthew Roberts

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Abstract

A production run of 5550 hermetically sealed cylinder assemblies with precision pressure relief burst discs will be assembled and laser welded at a manufacturing lab at Sandia National Labs. Production of these cylinder assemblies requires many steps, including piece part machining, geometric inspection, cleaning, subassembly, complete assembly via laser welding, and finally leak checking. While this production run is large enough to invest in process optimization and specialized tooling, it is not quite large enough to dedicate new lab space and specify equipment specifically for this job. This study will investigate process parameters and their effects on quality and process flow time, as well as a fixturing design study with the goal of reducing process time while maintaining quality requirements.

Introduction

Sandia National Labs is in the early preproduction, planning, and qualification stages of a new cylindrical pressure vessel product. The production run will consist of 5550 units, which include sufficient quantity for destructive qualification testing, spares, and future replacement and refurbishment. So far, a weld process parameter study has been conducted to ensure high quality full penetration welds. The selected parameters are carefully documented in a welding procedure that is revision controlled. Pre-production runs of this cylinder product have been completed in order to prove in the production process and evaluate quality control. Recently, estimates were made for cost and a rough production schedule. The estimates project the production schedule will last several years, due to the laser welding lab having other ongoing work and only being able to commit roughly 50% of their available time to this program. As a result, this project was kicked off to study the process and seek time and cost savings opportunities. For the purposes of this class, scope will be limited only to the laser welding of a pressure relief burst disc to the head of the cylinder vessel assembly. The time for a single unit to be laser welded and leak checked was provided to be 35 minutes. Shaving off only a few minutes can have a significant impact to cost and schedule due to the number of units in the production run.

Description of Process

The first step in this study was to gain an understanding of the entire laser welding process. The following is a description of the current process and weld parameters.

The laser welder is an ILT-1500 high precision fiber laser welding system with an FLW-D30 welding head. The laser is capable of 500W Continuous or 3000W Peak Pulsed. The laser welder has a build area of 200mm x 200mm X-Y and 150mm in the Z (height) direction and is equipped with an optional rotary stage. Motion stages have an advertised ±8um accuracy and ±8um repeatability, while the Rotary Stage is capable of ±80 arc-sec Accuracy and ±3 arc-sec repeatability.

The Laser Welder is set to Pulsed Welding (PW), which is a process where the part is momentarily held stationary for a single spot weld. Then the joint progresses a small increment with some amount of overlap with the previous weld so that a new weld spot can be made. This is repeated until the joint is fully welded. In the case of this product, the weld is autogenous, meaning filler material is not added to the weld. The weld pool only consists of the melted parent material. Shield gas is not used.

A study by Assuncauo et. al. attempted to compare power density and penetration between PW and Continuous Wave (CW) welding [2]. Figures 1 and 2 from [2] show plots of penetration vs power density.

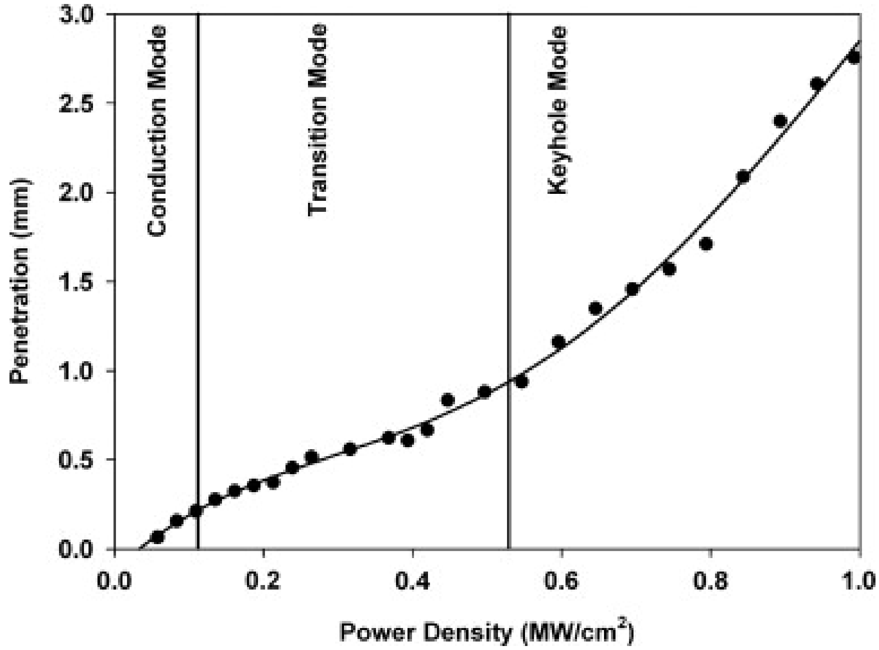

Figure 1: Welding Modes in CW Welding from [2]

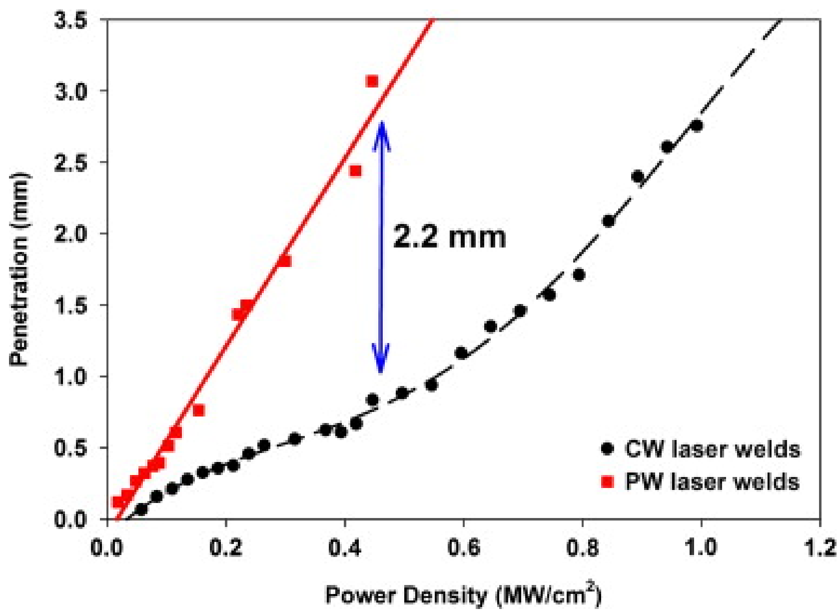

Figure 2: PW vs CW Penetration Plots from [2]

Figure 3 shows cross sections of laser welds at various power densities to demonstrate the Conduction, Keyhole, and Transition modes.

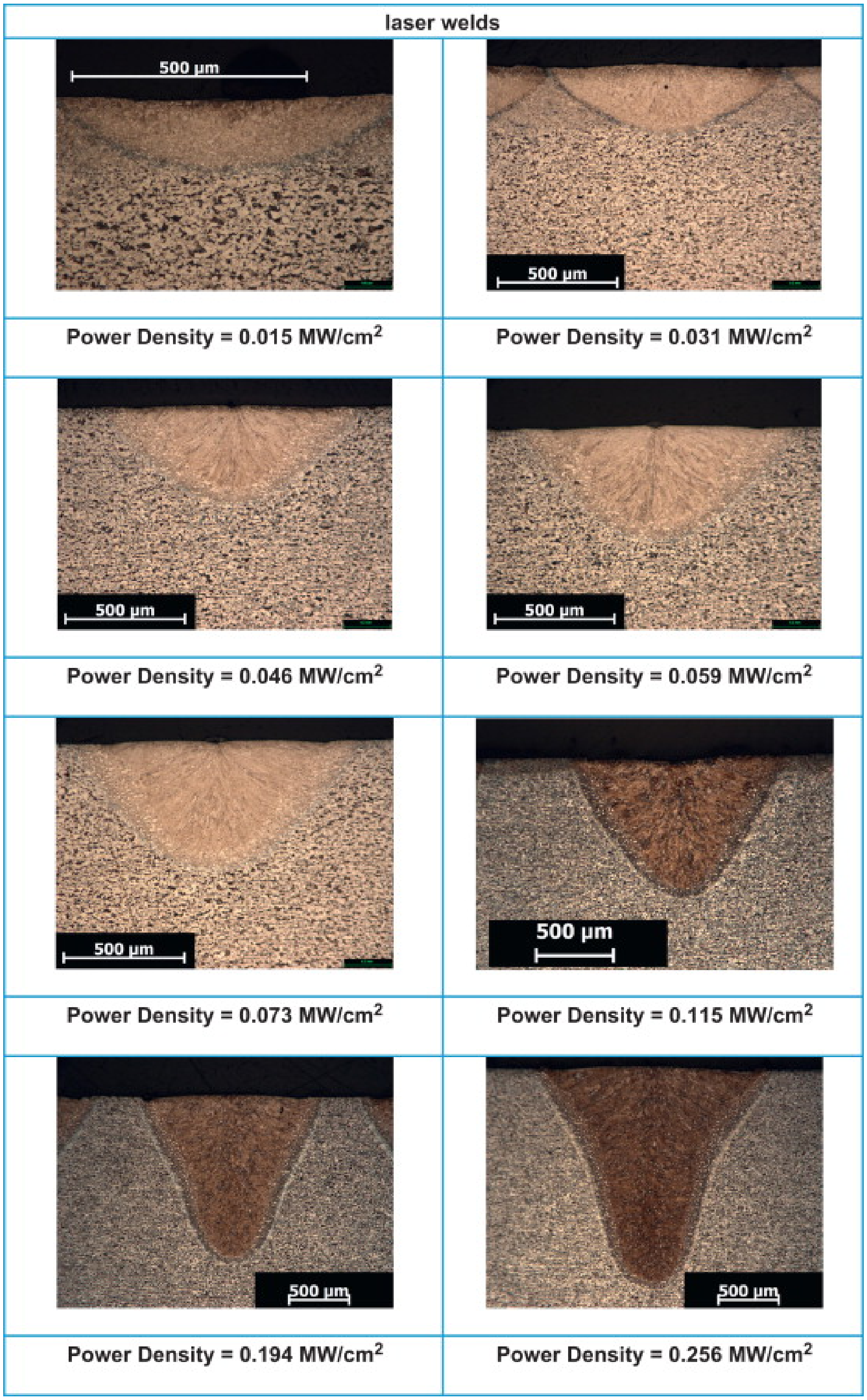

Figure 3: Cross Sections Demonstrating Weld Modes from [2]

It can be observed from these plots and cross section images that greater Laser power increases penetration and the shape of the solidification region. Power is therefore an important parameter to optimize and control in order to achieve the desired amount of penetration. In the case of this product, full penetration is required to ensure the burst disc does not leak under operating pressure, and bursts at the desired pressure.

Percent Overlap (PO) is another important parameter that was studied because it impacts “Effective Penetration” in a PW process. Figure 4 below demonstrates the geometric effect that Overlap has on “Effective Penetration”.

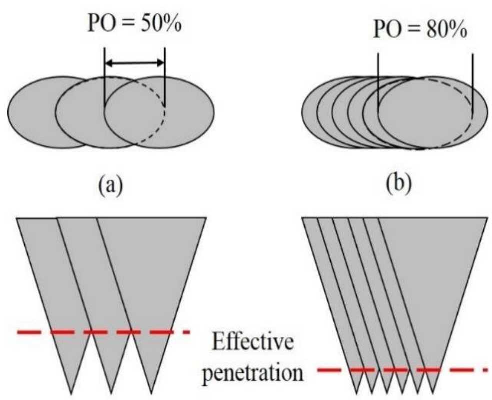

Figure 4: Effective Weld Penetration

With PW, there exists a cone shaped solidification region. The penetration depth measured along the joint will vary in a sawtooth pattern with peaks centered on the weld spots and troughs at the halfway point between weld spots. This sawtooth profile depends on both the bottom angle of the cone, which is a function of Laser Power, and the distance between weld spots, defined by PO. Greater PO results in greater effective penetration, measured as the depth from the surface to the troughs of the sawtooth pattern.

The current process is set to 80%-85% PO. The Power is set to 705W with a 100%_25%_15ms pulse shape, and the laser pulses at 5Hz. The Average power with these parameters is 101W. The Pule Profile is plotted in Figure 5.

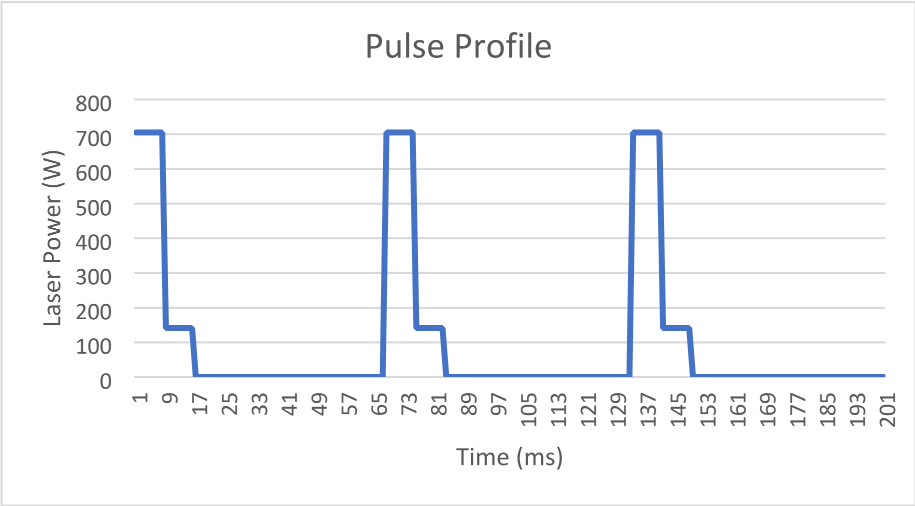

Figure 5: 100%/25%/15ms PW Pulse Profile

With a 1” diameter disc, a .016” diameter spot size, 80% OP, and 5Hz pulses, the total weld time should be approximately 3.3 minutes. This calculation is carried out using formulas described in [4]. See Figure 6, below.

$D := 1\ \mathbf{in}$	Burst disc diameter
$d := .016 \cdot \mathbf{in}$	Weld spot size
$O := 80\%$	Overlap to ensure fully joined hermetic seal
$PRF := 5\ \mathbf{Hz}$	Pulse repetition frequency
$V_{PW} := (1 - O) \cdot d \cdot PRF = 0.96\ \frac{\mathbf{in}}{\mathbf{min}}$	Feed rate for PW
$T := \frac{\pi \cdot D}{V_{PW}} = 3.272\ \mathbf{min}$	Time to complete weld at .96 ipm

Figure 6: PW Weld Time Calculation, using formulas from [4]

Fixturing

The Cylinder Assembly is installed in a custom fixture for burst disc welding. The inner diameter of the fixture is sized to be a slip fit with the outer diameter of the cylinder assembly. Clocking of the cylinder assembly is maintained by a clocking pin and corresponding hole at the bottom of the fixture. The fixture itself is attached to the rotary stage by an air collet. The rotary stage is fixed to the top of an X-Y stage. Prior to welding, the X-Y stages bring the seam of the weld to the fixed laser head. The weld seam is then progressed by rotation of the rotary stage.

The weld is done in 6 segments. The first three segments are welded in the first setup in the fixture, then the fixture lid is adjusted to allow welding of the remaining 3 weld segments.

Quality Control

Quality is maintained rigorously by controlling the process in a revision-controlled procedure. Cleanliness is ensured by a multi-step ultrasonic bath to prevent contaminants from entering the weld pool, which could lead to porosity. All Piece parts are fully inspected prior to assembly and final burst disc welding. Finally, the laser weld is qualified by 100% leak checking and 4% destructive burst testing.

For the most part, the welding process is automatically controlled by a custom routine programmed into the laser welder. However, some manual control of position is required to keep the seam tracking with the laser head. The laser welder is equipped with a vision system that provides the user with sufficient magnification to ensure that the weld spot is centered within ±.005” of the center of the seam, which is 0-.003” wide. Manual control to correct for runout is done by jogging the part in the X-Y direction through a Graphical User Interface. While it is not difficult to maintain seam position during a single weld, I recommend that this need for manual control be eliminated to reduce the likelihood of failure. This is a tedious job that will be completed by a single operator working for weeks on end producing 20-25 units per day.

Tolerance stack analysis of the cylinder assembly and the fixture revealed that runout greater than .005” is very likely. Much of this runout comes from Ovality of the body of the cylinder [1]. Unfortunately, this severely limits the ability to hold the cylinder in the correct location through fixturing alone. It is possible to introduce precision machined features that a fixture may interface with to reduce runout. However, at this phase of development, introducing new features could invalidate qualification tests.

The manufacturer of the laser welder makes an optional “Seam Finding” head that can locate a seam and hit the center with ≤10um accuracy. This seems like a great solution and should be investigated further for compatibility with this welding process. This optional attachment would eliminate the need for manual control during welding.

Process Flow Analysis

In order to target areas for possible improvement, a Process Flow was developed with the help of the operator. Time estimates for process steps were provided by the operator. The resulting Flow Diagram is display below in Figure 7.

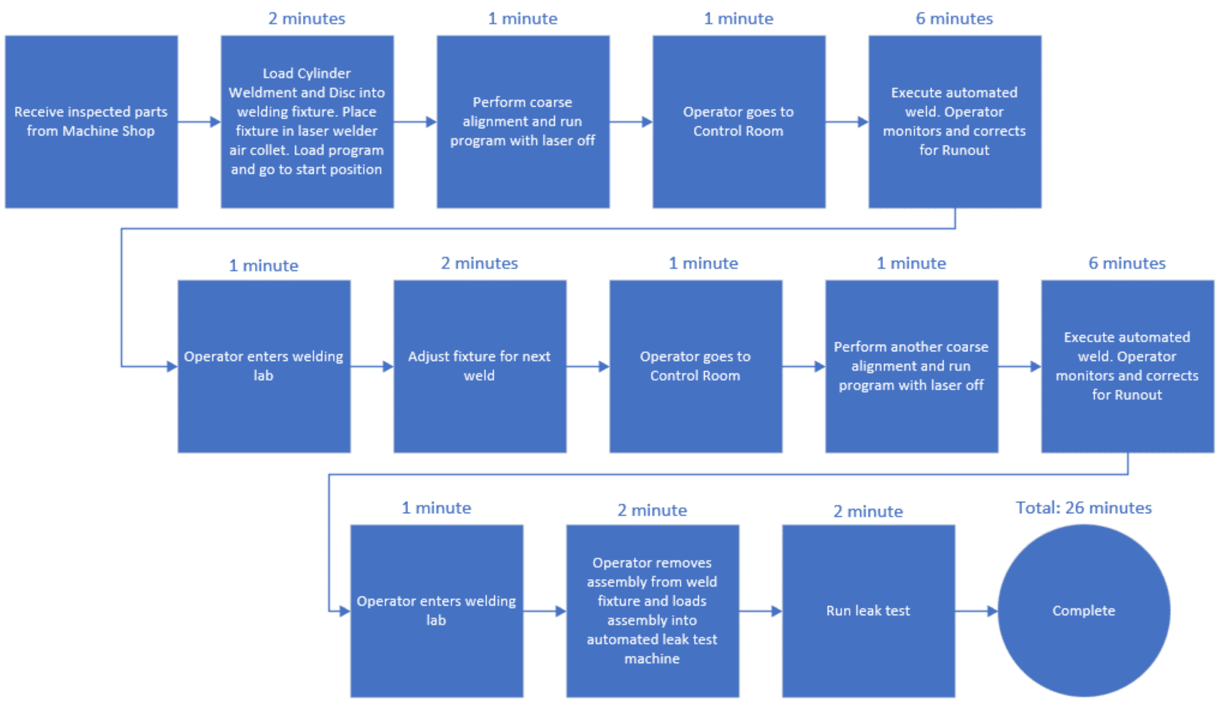

Figure 7: Process Flow

One unique aspect of this welding process is that the laser welder is in a lab that is used for machining of energetic materials. It is therefore necessary for operators to remotely operate any equipment in the lab. This can be seen in the process flow.

It should be noted that the estimated 12 minutes of welding time does not agree with the calculated weld time of 3.3 minutes. Also, the overall Process Flow estimate of 26 minutes does not agree with the 35-minute total process time that was provided at the start of this effort. It is believed that the 35-minute estimate included the entire time necessary to complete leak checking, but in production, leak checking runs in parallel with welding of the next burst disc.. It is also unclear whether the 35-minute estimate accounts for any down time due to union mandated breaks and other general distractions. It is therefore recommended to collect real world durations to refine this flow analysis and allow the product sponsor to make more informed decisions about the recommendations included in this report. To be conservative, 35 minutes is assumed to be the correct process time.

Following Process Flow Analysis, two main strategies for reducing flow time were considered: Fixture Design and switching to Continuous Wave Welding.

Pulsed Welding vs Continuous Wave Welding

The estimated 12 minutes of laser welding was initially considered as a highly attractive area of improvement. The Laser welder is capable of both PW and CW, and studies by Jason Berger, a welding Engineer at Sandia, showed that CW feed rates are up to 80 times faster than PW [3]. This would in theory reduce the weld time from 12 minutes down to 9 seconds. However, digging deeper in the calculations revealed that the 12-minute weld time was inaccurate. The calculated welding time of 3.3 minutes can be reduced to 2.4 seconds. While this may not sound significant. It is a roughly 9% reduction in schedule (relative to a 35-minute flow time) and a cost savings of roughly $63k when spread over 5550 units.

In addition to time and cost savings, there are advantages when it comes to mechanical properties of the weld. The same study by Jason Berger [3] investigates solidification cracking of laser welded Stainless Steel. The study found that PW is more likely to yield primary Austenite, which is prone to solidification cracking. This is due to preferential vaporization of relatively high vapor pressure alloying elements Chromium and Manganese, which results in a decrease in chromium-nickel equivalent ration. The Figure 8 below shows the relationship between Cr/Ni equivalent ratio and resulting microstructure.

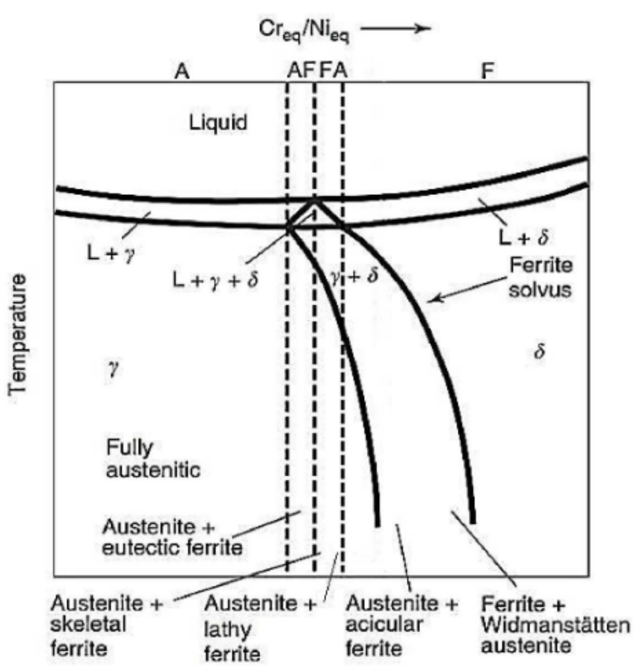

Figure 8: Pseudo-Binary Fe-Cr-Ni Phase Diagram, cited in [3]

The main drawback to switching to CW is that a new process parameter study would need to be conducted. Additionally, qualification testing has already begun, and changes to the weld parameters could invalidate evidence that was already collected.

Fixture Design Requirements

Fixture reset steps to weld the last three weld segments take an estimated 5 minutes, which is 14% of the total 35-minute flow time and costs approximately $98k when repeated 5550 times. These steps to reset the fixture are also somewhat tedious for the operator. Ideally, the operator would be able to set up the fixture only once, then execute the weld remotely and not need to monitor/correct for runout. A fixture design that stays out of the way of the laser beam during the full 360° rotation of the assembly would eliminate the need to go into the welding lab and reset the fixture.

One way to accomplish this is to use a hold-down finger mounted on a post that is not on the rotary stage. Hold down fingers like this are common in optical table fixturing and examples can be found on Thorlabs, as shown in Figure 9.

Figure 9: Thorlabs "PM4: Large Adjustable Clamping Arm"

One possible mounting location for the hold down finger is indicated in Figure 10.

In order to be an effective time saver, the finger should avoid the use of fasteners. Instead, cam action, pneumatics, or a bistable mechanical switch mechanism should be used to apply consistent pressure to the burst disc. At the interface between the finger and the burst disc, a bearing should be used to apply pressure in the thrust direction without rotating the burst disc relative to the cylinder assembly.

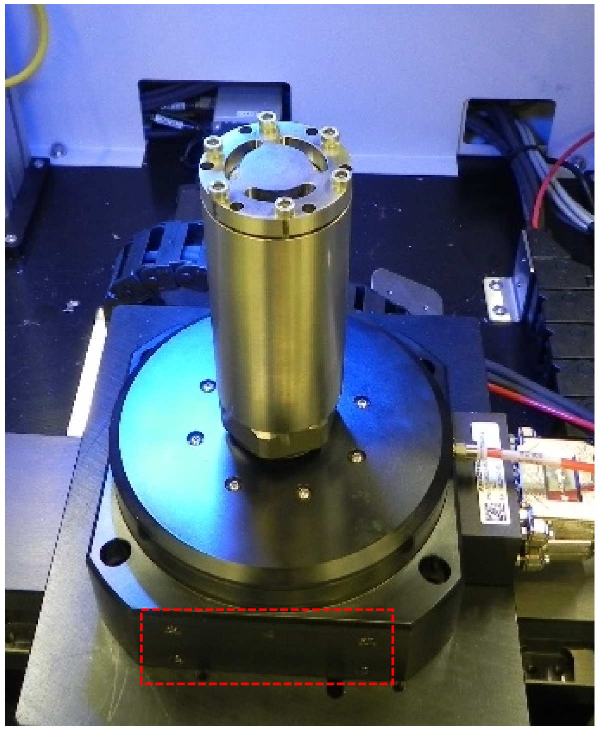

Figure 10: Possible Hole Pattern for Hold Down Mounting Locations

Conclusions and Future Work

The existing laser welding process was studied to understand possible schedule and cost saving solutions. Parameters that were considered include Power, Percent Overlap, and Continuous Wave vs Pulsed Welding. Continuous Wave may be able to reduce time by 9-11% and should be investigated further. A Process Flow Analysis was conducted to gain a better understanding of areas of improvement, which revealed that simple fixture design changes can reduce overall process time by 14-19%.

The next steps in this effort are to consider having multiple parts in a single setup. A few concepts have been brainstormed, but more work needs to be done to evaluate feasibility. This effort was not included in this report due to time constraints. If it is possible to have multiple parts in a single setup, throughput of the leak check device needs to be increased to avoid becoming a bottleneck.

Sources

1. American Society for Testing and Materials (2004). Standard Specification for Seamless and Welded Ausenitic Stainless Steel Tubing for General Service. ASTM International.
2. Assuncao, E. and Williams, S. (2013). Comparison of continuous wave and pulsed wave laser welding effects. Optics and Lasers in Engineering, 51(6), pp.674–680. doi:https://doi.org/10.1016/j.optlaseng.2013.01.007.
3. Berger, J. (2018). Effect of Preferential Vaporization during Laser Rewelding on the Solidification and Cracking Response of Type 304L Stainless Steel Alloys with Systematically Varied Manganese Contents. Thesis.
4. Coroado, J., Ganguly, S., Williams, S., Suder, W., Meco, S. and Pardal, G. (2021). Comparison of continuous and pulsed wave lasers in keyhole welding of stainless-steel to aluminium. The International Journal of Advanced Manufacturing Technology, 119(1-2), pp.367–387. doi:https://doi.org/10.1007/s00170-021-08226-5.
5. Ventrella, V.A., Berretta, J.R. and de Rossi, W. (2010). Pulsed Nd:YAG laser seam welding of AISI 316L stainless steel thin foils. Journal of Materials Processing Technology, [online] 210(14), pp.1838–1843. doi:https://doi.org/10.1016/j.jmatprotec.2010.06.015.