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Development of a Fiber Laser Welding Capability for a Firing Set

Federal Manufacturing & Technologies

Jose A. Samayoa

KCP-613-8748

Published April 2010

Final Report

Approved for public release; distribution is unlimited.

Prepared under prime contract DE-ACO4-01AL66850 for the
United States Department of Energy

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A prime contractor with the United States Department of Energy under Contract Number DE-AC04-O1AL66850

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KCP-613-8748
Distribution Category UC-42

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Jose A. Samayoa

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Final Report
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Abstract

Development work to implement a new welding system for a Firing Set is presented. The new system is significant because it represents the first use of fiber laser welding technology at the KCP. The work used Six-Sigma tools for weld characterization and to define process performance. Determinations of workable weld parameters and comparison to existing equipment were completed. Replication of existing waveforms was done utilizing an Arbitrary Pulse Generator (APG), which was used to modulate the fiber laser's exclusive continuous wave (CW) output. Fiber laser weld process capability for a Firing Set is demonstrated.

Summary

Weld characterization and implementation of a new fiber laser welding system was completed in support of Firing Set welding. This work was undertaken to supplement and backup two existing lasers in two departments. Workload studies provided justification for purchasing the extra machine to support production volume and to mitigate schedule risk for the project

The new capacity / backup laser is significant because it represents first-time use of fiber laser technology at the KCP. Fiber lasers are the state-of-the-art in the field of laser equipment. The system procured for the Firing Sets and AF&F is a CW, 2KW laser by IPG Photonics of Oxford, MA. Since the fiber laser operates exclusively in the CW mode, it was equipped with advanced pulsing technology to permit replication of existing sinusoidal and square waveforms matching those of the existing GSI, JK802 Nd:YAG lasers. Using the device, the new fiber laser was capable of matching the waveform outputs used for production.

The behaviors of weld penetration, weld width, "throat" and rewelds are shown for the new fiber laser. Weld groups per SS1A4542 were welded to cover qualification requirements for the 1A1099 assembly. These also satisfied most of the 1A1900 welds.

For this work, variables were minimized. Weld speed was held constant to existing levels, 70 and 80 IPM. Power levels were initially varied to characterize the range of usable parameters to achieve a target of around 0.027 - 0.028 inch weld penetration for butt joints excluding the TSL, which was targeted at 0.022" nominal. The statistical response for welds tested is presented with predicted process capabilities, which are shown to be compliant at a minimum 4.56 σ levels from nominal. Thermal testing of the ISL weld was done for comparative purposes indicating comparable temperatures that averaged 183.7 °C for the Fiber vs. 208°C for the existing YAGs. Visual results for the welds were shown to be acceptable. Metallography of the welds studied is presented for applicable weld groups in accordance with SS1A4542. Focus characterization is presented.

Discussion

This work was required to provide production welding parameters and implement a newly acquired fiber Laser system. An earlier capability of two lasers had been commissioned in 2006 and 2007; however, work load studies indicated the need for further production capacity. Justification for a new third laser was based on this need.

Selection of the fiber Laser was motivated by the desire for greater reliability and simplicity. The previous CW Nd:YAG lasers had been maintenance-intensive. In contrast, the fiber laser offered increased efficiency, simplicity of design via elimination of hard cavity optics resulting in lower maintenance and, reportedly, improvements in process. A new equipment integrator, Innovative Laser Technologies (ILT) of Minneapolis, MN, was utilized. Familiarity with this contractor's motion software facilitated the programming work. Translation of programs across systems was delegated to the vendor to expedite the process. Most individual geometries and base-line programs from the existing laser welders were converted for use with the fiber equipment.

Much research into fiber Laser technology was done prior to this procurement including visits to manufacturers and completion of welding trials at vendors' sites. A PDRD research project[1] was completed to investigate the viability of the technology for use at the KCP. Trips were made to fiber laser users, integrators and manufacturers. Medtronics Corporation demonstrated applications of the technology in manufacturing. The Edison Welding Institute demonstrated a system at their facility and was commissioned to perform weld evaluations. Other weld trials were done at IPG Photonics, Alabama Laser and Innovative Laser Technologies (ILT) in Minneapolis. Summaries of these visits are included in the "References" section of this report.

Scope and Purpose

The work scope included the completion of qualification welds and their evaluation to satisfy weld requirements for production in accordance with SS1A4542, Welding Requirements, MC4702[9]. The work required characterization of a new fiber laser and development of specific weld parameters to satisfy the stated criteria. Certification of samples involved the production of welds for up to seven unique groups using the new parameters. The welds had to comply with visual criteria and strict penetration and porosity limits as verified by metallography. Compliance to criteria and statistical analyses of process capability were completed. Visual inspection of welds was completed by inspection. Operators were qualified and a third alternate tool, FW414282-403, was fabricated.

To expedite and facilitate the work, the concept of group qualification was used. The concept, defined under weld specification SS1A4542, allows combining like-joint configurations, precluding qualification by individual weld type. This method reduced labor and hardware cost by about 60% and allowed completion of the work within a compressed time frame.

Micrographs of over 50 metallurgical sections from welds made on WR housings were taken and over 140 Snap Plates (S/P) penetration measurements were completed. To optimize use of available hardware, dissimilar parts from equivalent groups, as allowed by the weld specification, were welded to fulfill the quantity requirements. Completed qualification welds were visually inspected and accepted.

Completion of this weld development report and a Welding Procedure Qualification Record (WPQR), listing machine parameters for developed welds, are also required by SS1A4542. This report contains both the WPQR and the development data in combined form. As required, conclusion and issuance of this report, contingent on DA approval, qualifies the fiber laser, CE214603, for production welding of the Firing Set.

Prior Work and Background

With the primary welding laser (CE212289) being at full capacity during 2006, an additional machine (CE213393) was planned and implemented during 2007 in an annexed location. This new laser (CE213393) was bought in 2005 and duplicated the department's primary welding system. Newer laser systems were technically updated with new MKII power supplies, improved controls, better viewing optics and a faster shutter. The shutter was capable of 0.020 sec cycle times compared to 0.150 sec previously. The new optics system incorporated additional capability to interrupt motion if impact occurred within the three-dimensional work space.

Two reports[11, 12] were published covering the implementations of CE212289 and CE213393. The reports are available as "Green Backs" and listed in the "TRIM" data base of the KCP.

Fiber Laser

The decision to purchase a fiber laser hinged on the desire for better reliability, repeatability and lower maintenance. Alignment issues are often a factor with lasers that utilize hard optics. One appeal of the fiber laser is the lack of internal optics, which negates alignment issues in their entirety. No hard optics exist internal to the resonator and amplifier.

The fiber laser also has superior beam quality and lower divergence due to the "rifling" effect of the beam-generating amplifier-and-resonator portion of the fiber length. Because it can be up to 20 meters long, it helps collimating the beam.

A comparative decision matrix, Table 1, was created to weigh the characteristics of the YAG and fiber systems. Price and availability issues further influenced the decision towards procurement of a fiber system. The IPG Photonics brand was chosen because of its ability to generate high power, a characteristic unique to this manufacturer and proprietary in the industry.

This fiber laser system is also equipped with switchable beam deliveries, one of which passes the beam through a ScanLab head. The ScanLab head is a galvanometer system rated at maximum output and capable of high-speed marking and welding by rastering the beam without moving the work.

Category	CW:YAG PLUS	CW:YAG MINUS	FIBER PLUS	FIBER MINUS
Processing General	1. Has processing precedent, established weld development, parameters, documentation, programs. 2. Quickest on-line implementation, lower engineering labor due to pre-exiting process 3. Good, known welding characteristics suitable to product.	1. Reported power fluctuation issues. 2. Updated JK802SM design uses DC vs. AC supply, identical cavity design but no field history - reportedly same process capability.	1. KCP weld testing indicates potentially capable system. 2. Newest state-of-the-art technology, highly touted as desirable by welding community.	1. Requires more development. 2. Highest engineering labor/material costs, additional sample hardware. 3. Longest to "on-line" implementation due to more development, parameter selection, report writing, DA buy-in. DA is favorable to Fiber technology.
Process Capability	1. YAG has established process capability.	1. Output power performance requires re-tuning procedure to "re-center" the process.	1. Linear power response with R^2 of near 1.	
Laser Capability 1	Sine and Square wave with Super Modulation (SM). SM peaks double machine power output.	1. ~3% efficient 2. Large cone angle 3. Need a shutter.	1. ~10X more efficient than YAG 2. Has best beam quality 3. Small included cone angle allows improved part access. 4. No shutter req'd 5. Has interactive modulation using Arbitrary Pulse Generatot (APG) to create wave forms.	
Laser Capability 2			1. For a given spot size, fiber laser has approx. 2 - 3X the focal length and depth of field, thereby improving focus insensitivity.	
Maintenance	KCP personnel has repair experience.	1. Requires tuning, flash lamp replacement 2. Communication issues. 3. Frequent maintenance attention required 4. GSI has reduced support network in USA now	1. Reportedly negligible maintenance. 2. No cavity alignment req'd. 3. No lamps or other components that degrade	1. No experience, LED bank repair by module replacement, but may be done in the field.
Facility		Largest foot print, largest chiller	1. Smallest foot print, smallest chiller 2. Most portable	
Cost		Most Expensive- ILT: $647,836 Alabama: $1,035,000 Unitek: $1,395,250 (funded for $850,000)	Cheapest- ILT: $562,846 Alabama: $930,000 Unitek: $1,515,500 (funded for $850,000)	

Table 1. Pro / Con YAG-to-Fiber Decision Matrix

Activity

As a precursor to this development, a weld penetration baseline of 0.027 - 0.028 inch was targeted for the non-TSL seams. This selection was based on previous experience and the production success achieved with the Nd:YAGs, which use penetration plus-biasing in their operation.

The CE212289 development activity had produced a nominal penetration of around 0.0257, which was central to the tolerance band, and a standard deviation of 0.0027 inch. The second system, CE213393, produced slightly improved nominal penetration of 0.0262 inch and a standard deviation of 0.0021 inch.

In order to increase the process margin for the /S/ Lower Specification Limit (LSL), “plus-biasing” of the weld penetration was gradually introduced for both current YAG systems, considering that no resulting degradation to the product was evident. Given this approach, the current operating range is set to 0.026 – 0.029 inches, or 0.002 – 0.004 inches above the specification range nominal.

The same operating range was adopted for the Fiber system excepting the TSL, which has a lower penetration requirement of .010 - .030 inch. For this application a penetration of 0.022 inch was targeted, 10% above nominal.

The uncentered performance not only enhances process capability for the lower side of the specification, but also reinforces insensitivity to weld fit up and process variation.

Standard Deviation Comparison

Figure 1, captures the progression of penetration ranges and resulting standard deviations for qualification seam welds by laser CE#s between CY2006 and CY2010. A distinctive trend is noted that indicates improvements in the standard deviation numbers going across machines from the YAGs to the latest Fiber equipment, which displays the least variation.

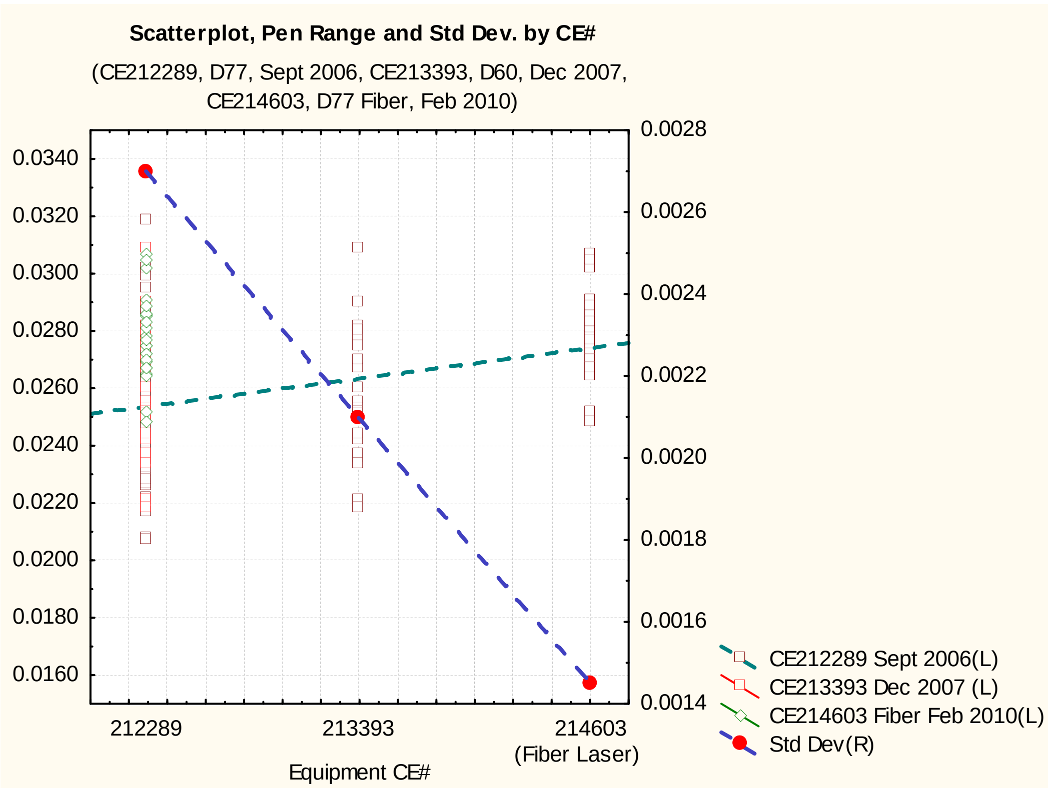

Figure 1. Distribution of Weld Penetration Values from Weld Qualifications and Resulting Standard Deviation Numbers for Each Group

Porosity Performance by Lens Focal Lengths

Lenses including 120, 160 and 250mm were tested. Prior to equipment arrival at the KCP, bead-on-plate (B-o-P) weld trials specific to the 120 and 160mm were completed at ILT's facility in Minneapolis. Pore measurements internal to the B-o-P sections indicated that porosity decreased with higher modulation frequency and longer focal lengths[8]. Encouraged by the results, testing was extended to the 250mm, expecting an even better weldability. Concerns over poor coupling with the longer lens did not materialize. The 250 mm lens produced the least spatter, optimum weld appearance and superior work clearance. Going forward, the 250 mm lens was selected for the development work and welding of qualification parts.

Sections made with this lens exhibited minimal to no porosity and produced the widest weld from the largest focused spot diameter of 312.5 microns. In comparison, the other lenses have spot diameters of 150 and 200 microns, respectively. Large focused spots influence weld width enhancing insensitivity to weld gaps and other fit-up issues. The YAGs 120mm lenses have a comparative spot size of 240 microns.Figure 2 shows porosity response at 48% and 300Hz.

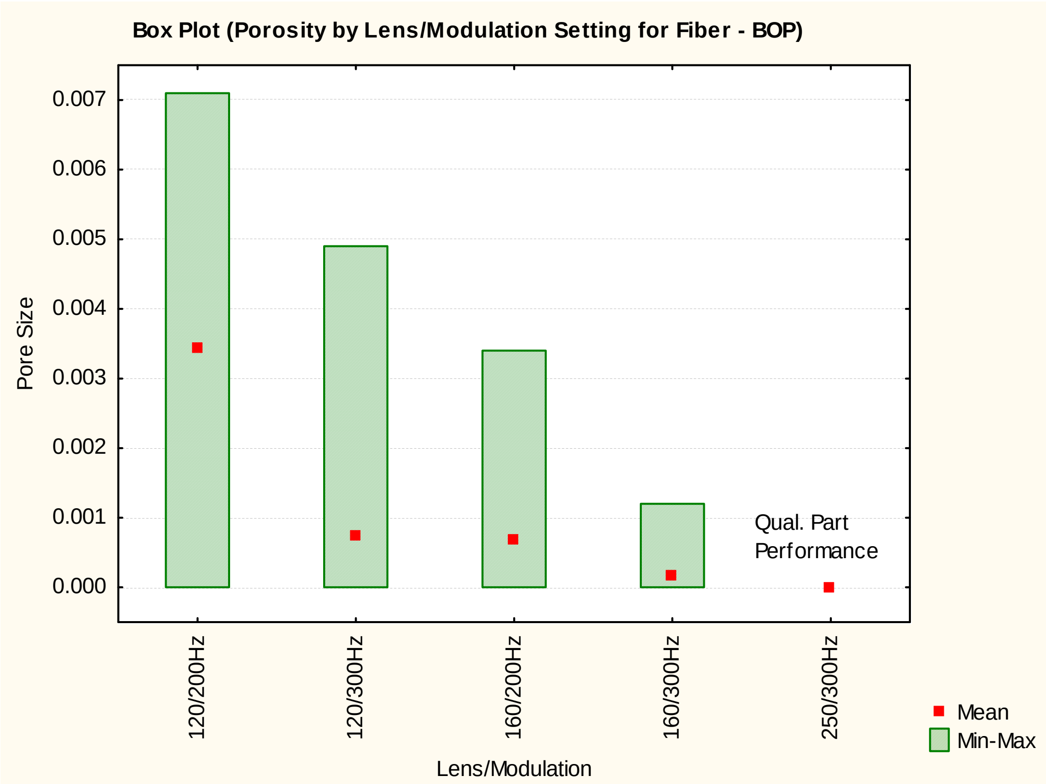

Figure 2. Porosity Performance by Focal Length

Focus Characterization

Focus characterization was completed prior to the startup of qualification welding.
To characterize true focus position for the selected 250 mm lens, a nominal power of 48% was used to produce an average 0.028" weld penetration (using ILT's true focus recommendations). From this work position, multiple snap plate welds were made at varying "Z" displacements in 0.010" steps from -0.140 to +0.140 inches. A new true focus setting was calculated, indicating close correlation but a negative offset of 0.010 inch from ILT's prescribed value. See Figure 3. The focus setting was adjusted to the new true focus to qualify parts.

Focus testing indicated a large depth-of-field for the 250 mm lens. Greater dispersion of penetration values was observed when moving away from the work vs. moving into the work, as is typical. A change of ±0.050 inch from true produced a minimal loss of about 0.001 inch in penetration. On average, about 0.010 inch degradation in weld penetration was noted at a bilateral defocus of 0.130 inch.

In comparison, the existing YAGs use 120mm plano-convex lenses with a 70% shorter depth of field and are more sensitive to focus position. The fiber laser uses an AR-coated, achromatic doublet lens. These lenses are nearly free from aspherical aberration and coma. Compared with singlet lenses, achromatic lenses have superior optical performance.

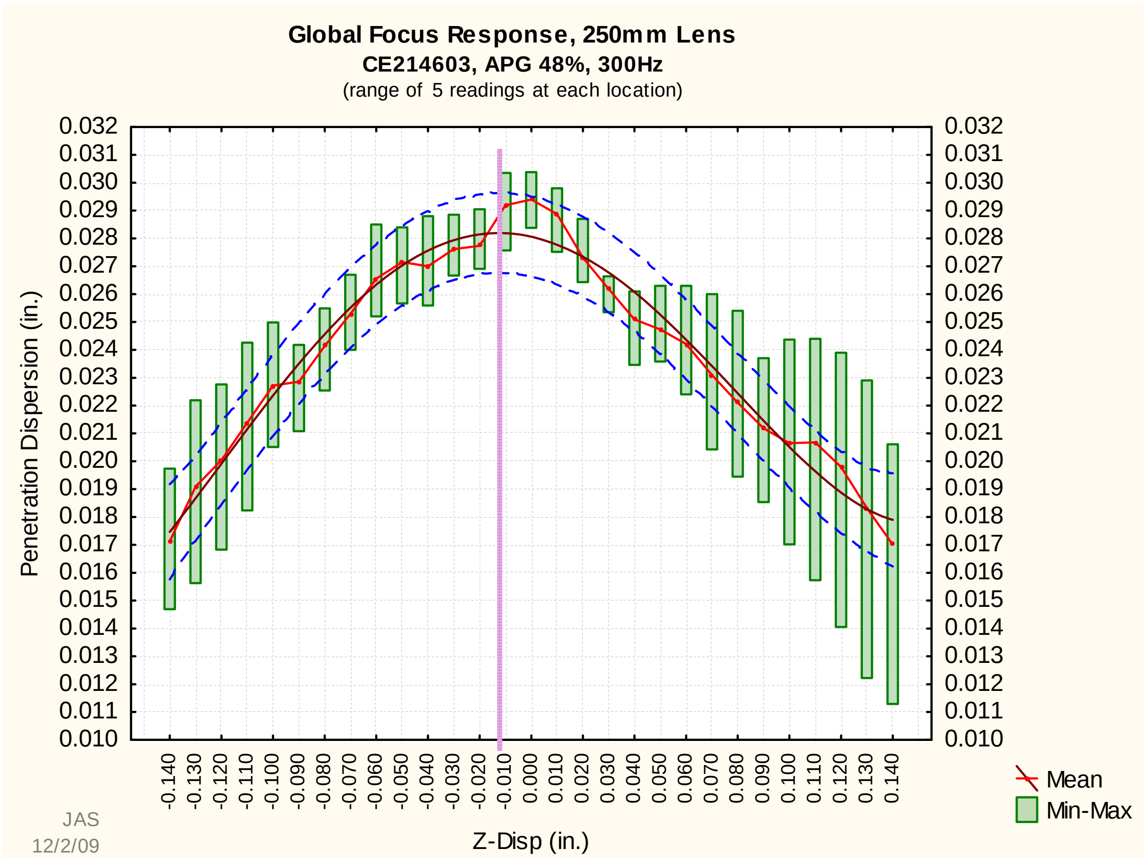

Figure 3. Focus Characterization

Welding Experimentation

Since equivalent performance to the old equipment was paramount with the Fiber laser, efforts were made to duplicate previous settings and wave shapes as much as possible.

The existing Nd:YAG, GSI JK802, laser equipment in the departments uses a sinusoidal modulated output at 300 Hz with 50% depth. The need for a modulated output presented an initial problem for the fiber's CW-only output.

On recommendation of the fiber laser manufacturer, an Arbitrary Pulse Generator (APG), fabricated by Dave Cimma LLC of Belchertown, MA, was incorporated to duplicate the modulated waveform values of the GSI, YAGs. The following is a description of the Cimma pulser from the equipment manual[10]:

> *The APG is a software and hardware package that allows creation of arbitrary pulse shapes and sequences typically used for laser processing. Pulse shapes are defined by creating a series of data points, giving the time and amplitude of each point. Up to 128,000 data points can be used to define a single pulse shape. Each pulse definition consists of not only the shape data points, but also the operating mode desired for use: free-run, burst, single shot or CW. Along with that information is the pulse rate and burst count. By selecting a pulse definition, all operating parameters are set. An external interface provides full remote control of pulse definition selections and APG functions via the CNC or other control system. Selection of one of seven pulse definitions, remote analog scaling of the pulses and various user-definable I/Os for welding is possible.*

Design-of-Experiment (DOE)

Welding experimentation replicated feed rates using values of 80 IPM for butt seams and 70 IPM for fillet joints, typical of the Reset Rings. Whenever possible, equivalent power settings were employed. Selected power levels fell within limits of the old range. To enhance robustness at the Lower Specification Limit (LSL), slight upwardly biasing of power levels was incorporated, as has been discussed. Setting many parameters to the old constant levels simplified the analysis. Only the behavior of weld penetration as a function of power and machine percentage output remained to be characterized.

The linearity of power (W) by "%" Power output was initially tested for comparison to the existing lasers. The GSI equipment has less-than-perfect linear output due to confocal regions where the output tend to "flatten" over small power ranges disrupting the response. The fiber laser had been reported as having near perfect linearity so, initially, the power vs. % output response was tested to verify the claimed performance. The response is shown in Figure 4. The regression analysis indicated a surprisingly good response with a near perfect algorithm approaching R^2=1.

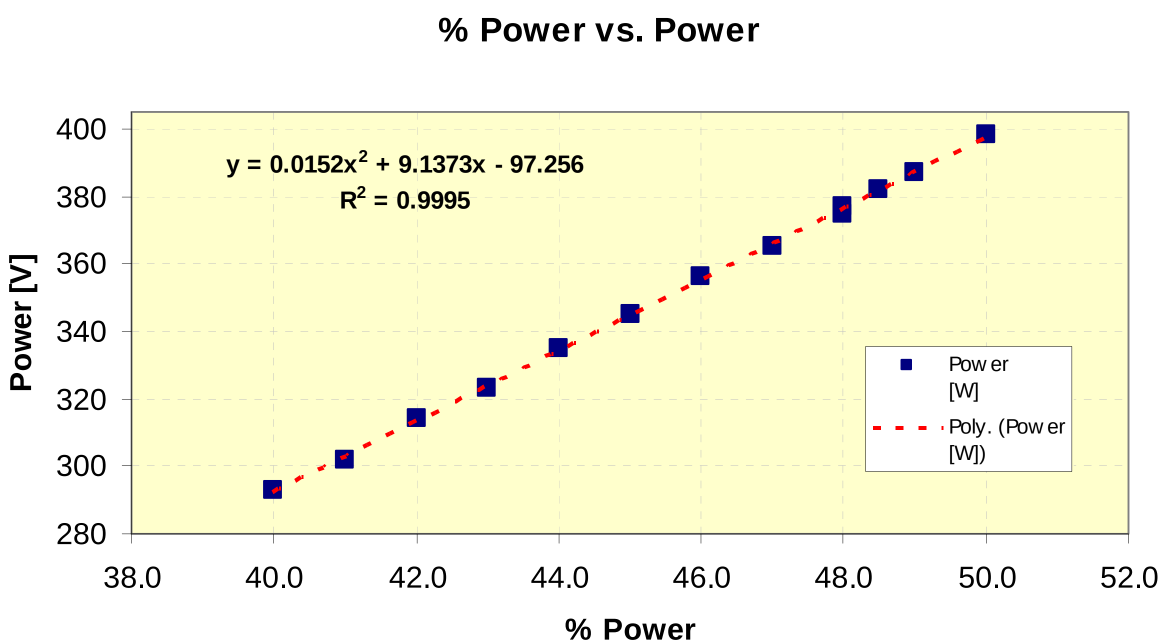

Figure 4. Power Output by Output % Setting Showing Excellent Linearity

Power output "%", the programmed value for the fiber laser, became the only parameter that was varied, facilitating the characterization activity. Power output was captured using an Ophir-Spiricon, water cooled meter, model #L1500W. The model #L1500W has a manufacturer's reported accuracy of ±5%.

The IPG's built-in internal meter is unsuitable for measuring modulated power due to its fast response. Further, the lack of a shutter and beam dump discouraged its use, typically requiring an absorptive metal mass as a "beam dump" substitute. The thermal pile Ophir averages the power over time and is suitable for modulated power measurements.

The initial power "%" range of 40% - 50% was chosen from previous screening tests done at the vendor, which had indicated usable penetration for the Firing Set welds.

A sinusoidal modulation of 300 Hz and close to 50% depth, same as the YAGs, was programmed into sector “4” of the Cimma pulser and held constant.

Both penetration and width responses by “%” power were charted, in accordance with Figures 5 and 6. Each point represents an average of four measurements per snap plate.

Good linearity is noted as evident by a high R^2 of .9932, suggesting the algorithm is acceptable as a predictor of values.

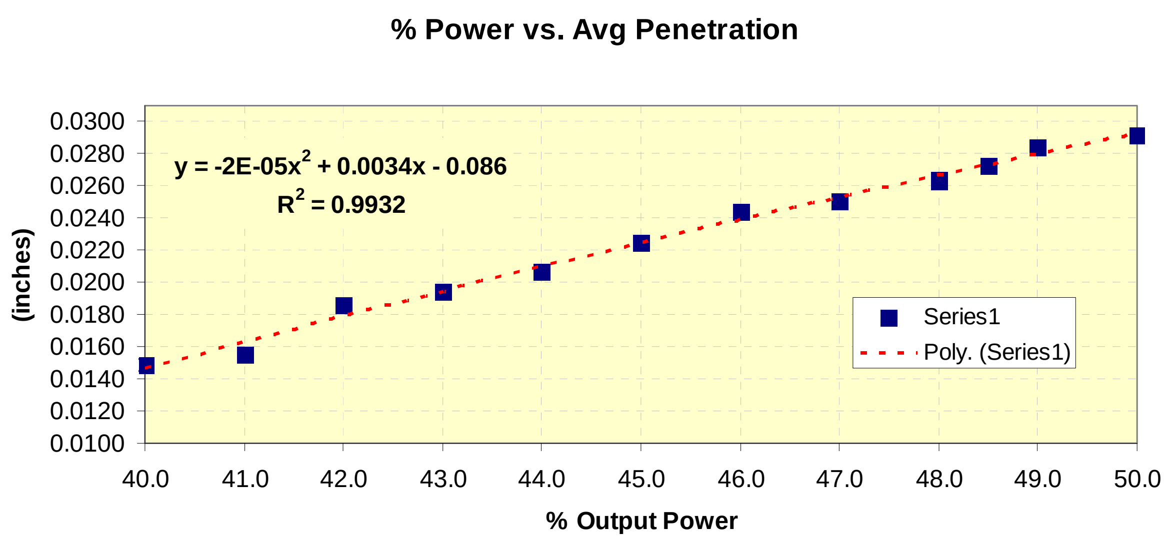

Figure 5. Output Power % by Weld Penetration, S/Ps

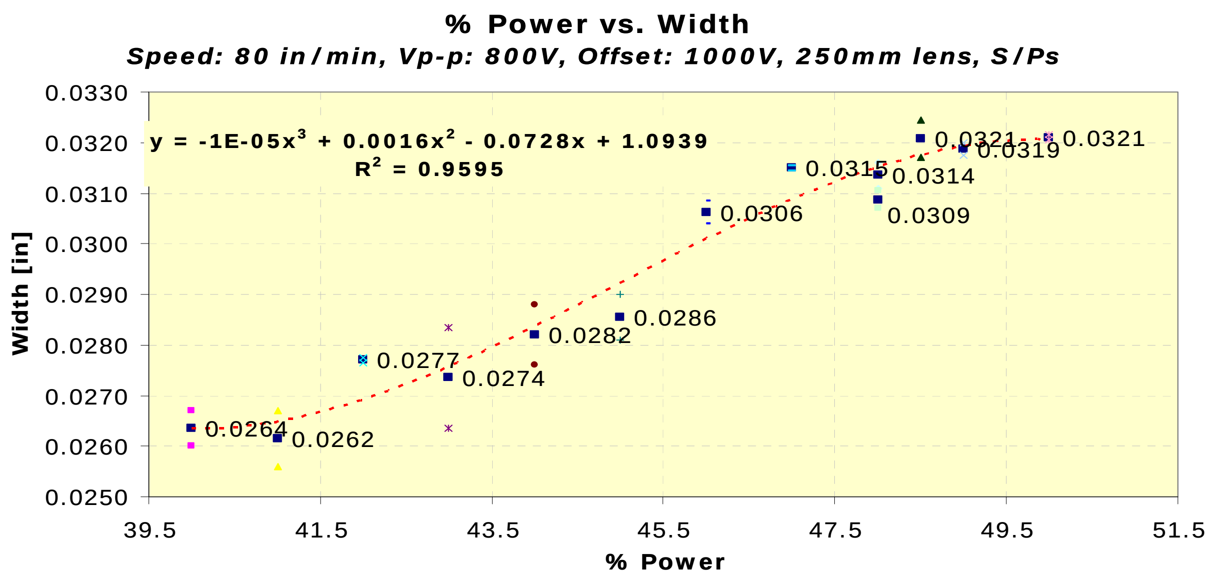

Figure 6. % Power by Weld Width, S/Ps

A more extensive penetration by actual power (wattage as read from the Ophir meter) was generated next, covering a longer period of about 6 weeks. Additional interim power values and multiple trials were charted with a broader range of 129 penetration readings. This exercise was a first-attempt to establish laser repeatability over time. The data was also reduced to determine the predicted interval (PI) at a 95% confidence level, as captured by the dashed line interval in Figure 7.

The PI represents worst case values expected from the response over ±3σ distribution. From the chart, a PI interval of ~±0.0015" is predicted, suggesting a standard deviation for the S/Ps of 0.0005 inch.

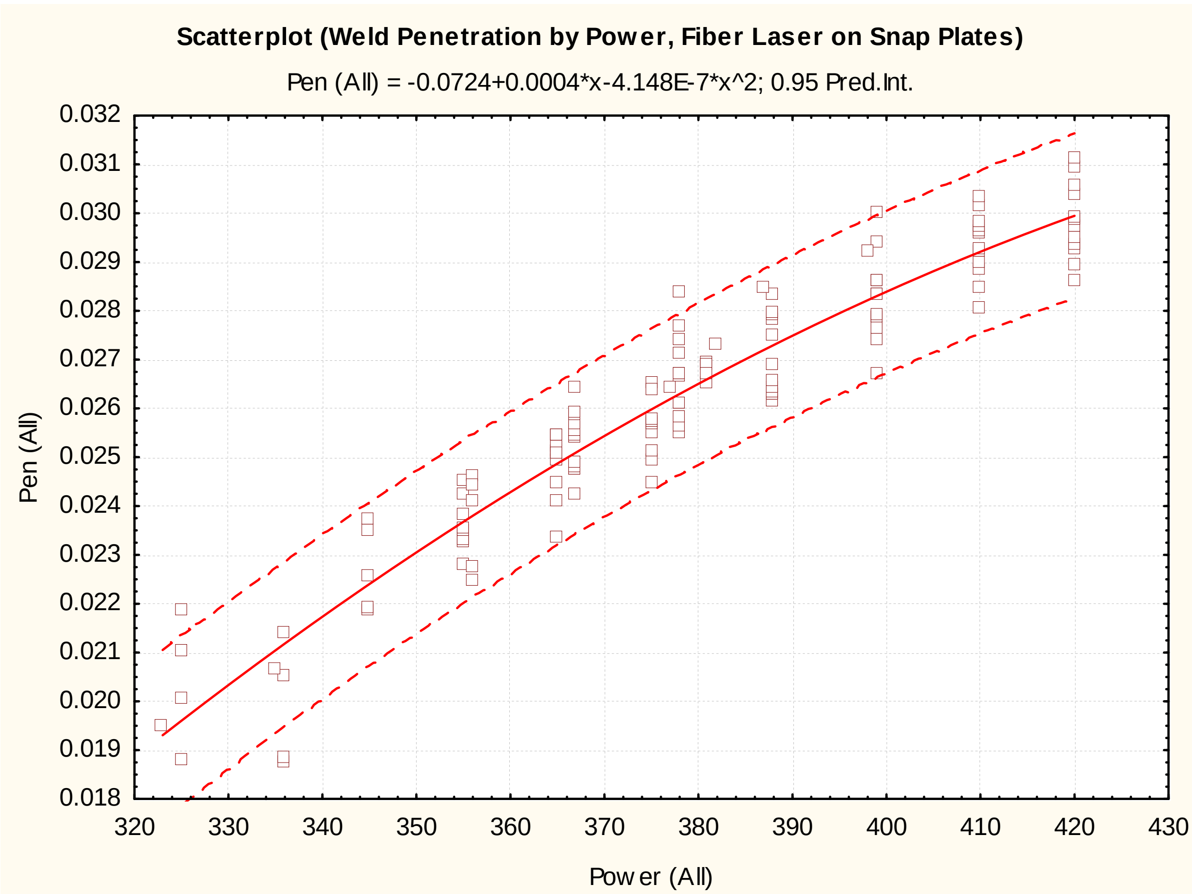

Figure 7. Extended Penetration Testing by Power in Watts, S/Ps, Showing a PI

Welding of Qualification Parts

Using the Figure 7 chart values, a power value of 48.5% or ~385 W, yielding about 0.027 inch was selected to weld qualification parts. These power and weld penetration levels correlate closely with existing YAGs parameters as used for production welding.

Initial simulated sample trial welds on samples using the chosen 48.5% produced penetration values that were 0.0015 inch higher than those measured on the S/Ps, indicating a negative S/P-to-SIM penetration shift. See "Sample Means" in Figures 8 and 9. A downward correction to 48% to lower the penetration was made. The new setting reduced the overall nominal penetration to 0.0281 inch, the value used going forward to weld qualification samples.

Twenty combined weld sections taken from Reset Rings (butt), J3, J7, J8 and Launch Accelerometer welds produced a standard deviation of 0.00153 inch. See Figure 8, "Non-TSL Seam Welds Process Capibility."

Process Capability Charts for Butted Seams and S/Ps

Graphical representations of process capabilities for the combined butt joints and for S/Ps are shown Figures 8 and 9. In all cases, an Anderson-Darling normality test was completed first and verified normality for the distribution of values. For the non TSL seams, an expected overall performance of 2.72 PPM is predicted. Zero PPM is predicted at the low limit. For the S/Ps, zero PPM loss is predicted at the lower limits. The specification minimum penetration for S/Ps is defined as 0.020 inches unilaterally with respect to the low limit.

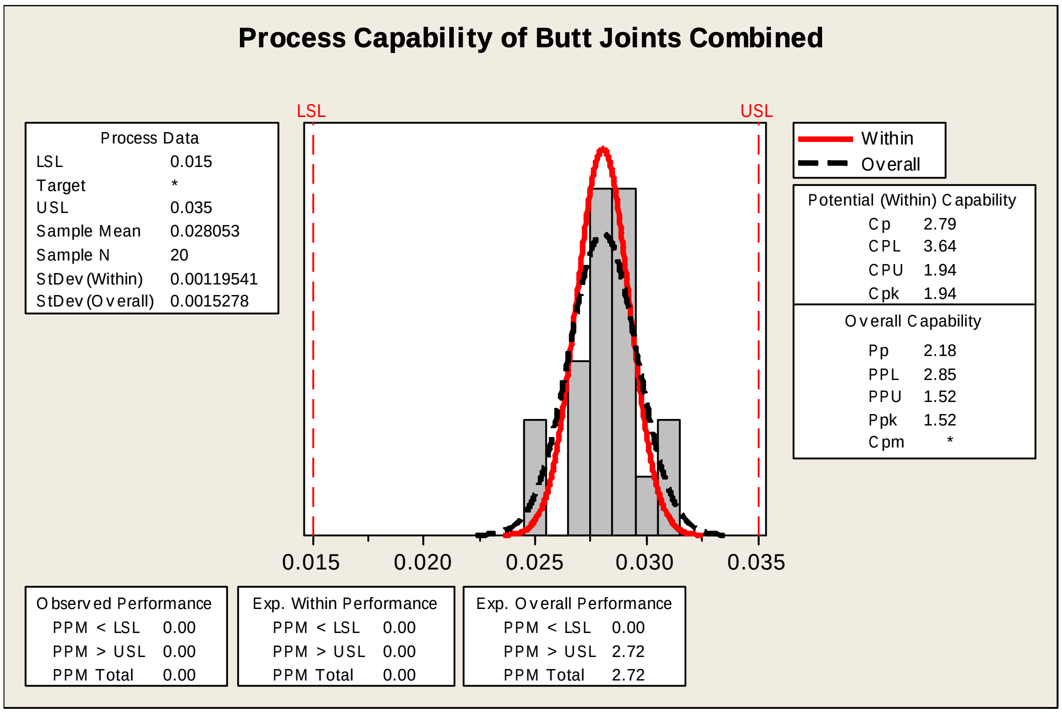

Figure 8. Non-TSL Seam Welds Process Capability

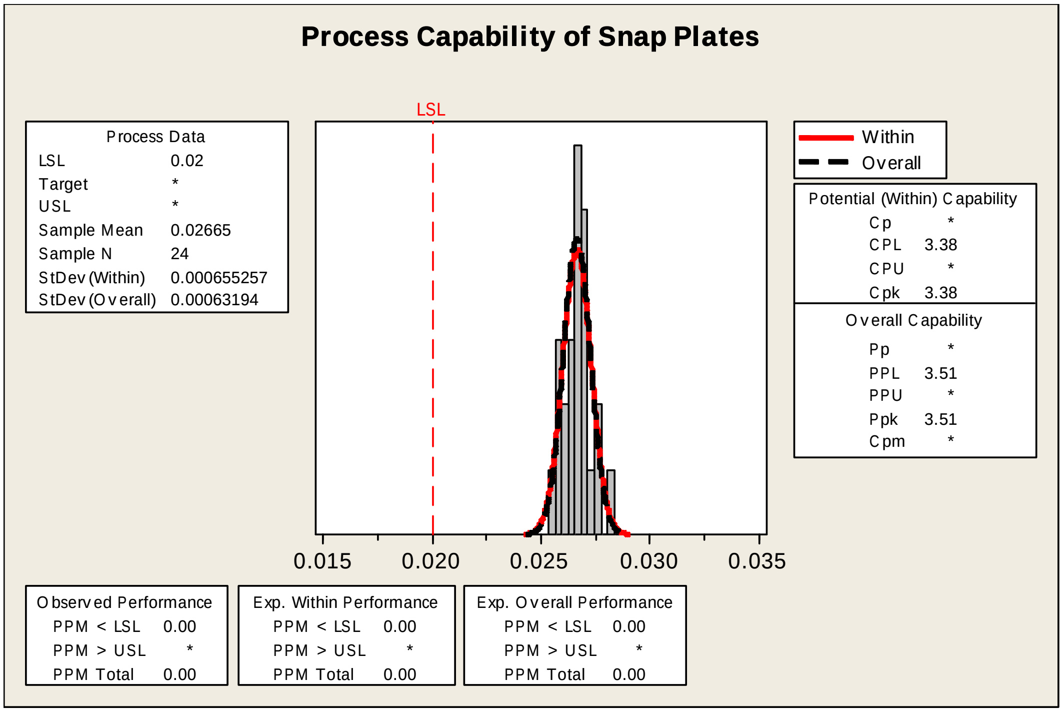

Figure 9. Snap Plates Process Capability

TSL Qualification Welds

Due to the Fiber laser's lower divergence and smaller raw beam diameter, perpendicular access to the TSL recessed joint is made possible. This characteristic facilitates processing and eliminates "canting", which is required with the GSI YAGs to provide beam clearance for a wide beam cone of 24°. In contrast, the Fiber's 2.8° included angle easily accesses the recessed TSL joint without interference. An excellent M^2 value and good coupling characteristics permit the use of a 250 mm lens to provide clearance vs. the shorter 120 mm for the GSI lasers. The comparison below compares YAG vs. fiber beams on the TSL joint. The YAG beam without "canting" interferes with the wall. The narrower fiber beam profile easily clears the side wall.

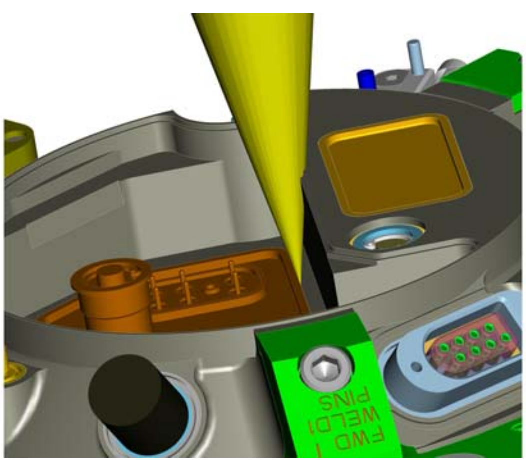
Figure 10. GSI YAG Beam Geometry

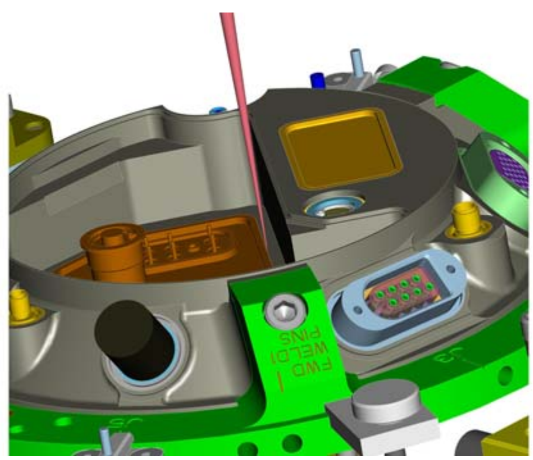
Figure 11. IPG Fiber Beam Geometry

The TSL penetration requirement is unique due to its lower specified range of 0.010 - 0.030 inch. With the YAGs this weld was made at the same power but with lower penetration efficiency due to the angled access. With a new 90-degree access, a lower power selection was possible and cooler weld temperatures for the TSL should result. Referencing the S/P penetration in Figure 5, a power level of ~45% in the range of 340 to 350 watts was selected to achieve ~0.022 inch weld penetration.

To validate the weld setting on actual parts, a scrapped TSL and simulated sample were welded with multiple segments using varying power "%" levels from 41% to 48%. The penetration responses are shown in Figure 12 along with the corresponding S/P data. Approximately +0.001 inch shift from S/P to product is noted. A value of 45% was chosen to achieve ~0.022 inch penetration overall on the qualification parts. Figure 12 shows the penetration response with corresponding weld width in inches.

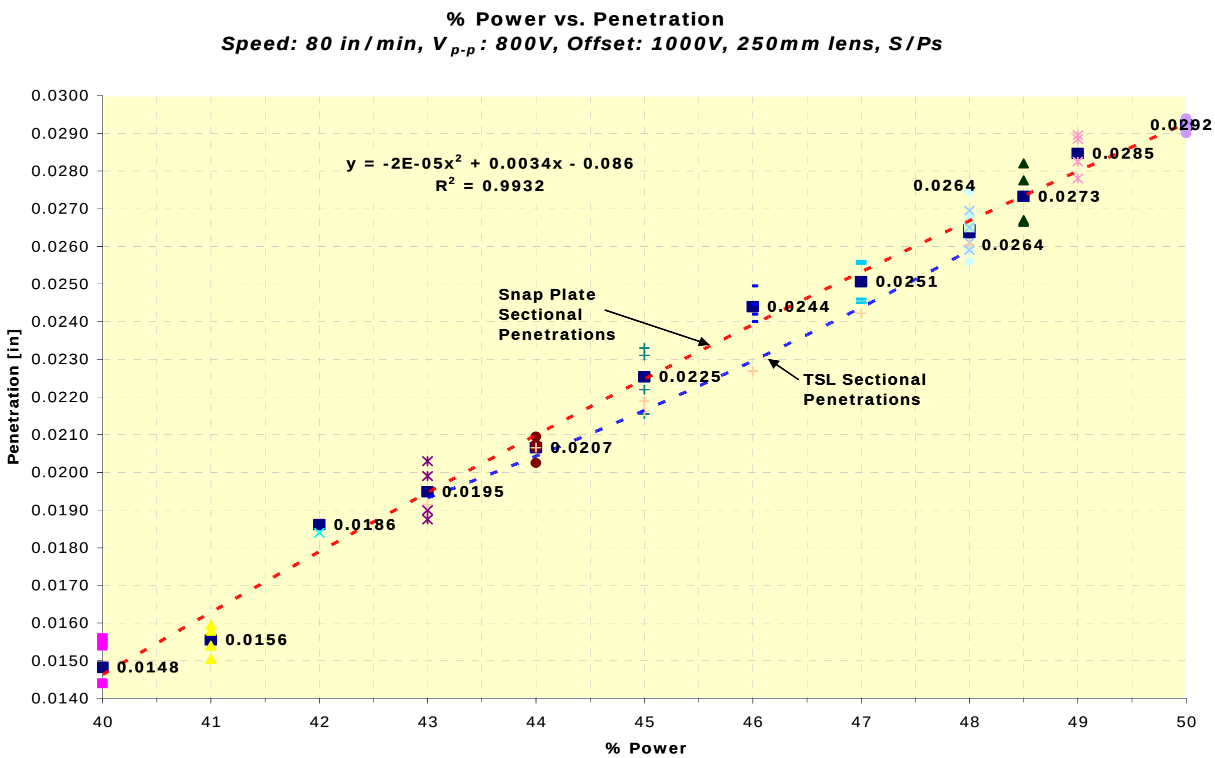

Figure 12. TSL Penetration for Various Power % as Measured on a Simulated Part

TSL Qualification Parts Welding

For qualification, two VAR TSL housings were welded onto two VAR 1A1067 Firing Set housings. Seven sections were taken from the weld periphery as follows: two each from the long sides and one each from the shorter segments. The fourteen penetration values obtained were analyzed for process capability, as shown in Figure 14. Robust process capability and a predicted performance of zero PPM rejects are predicted. The overall standard deviation for penetration for the qualification samples is 0.001285 inch, which is under the value of the combined joints.

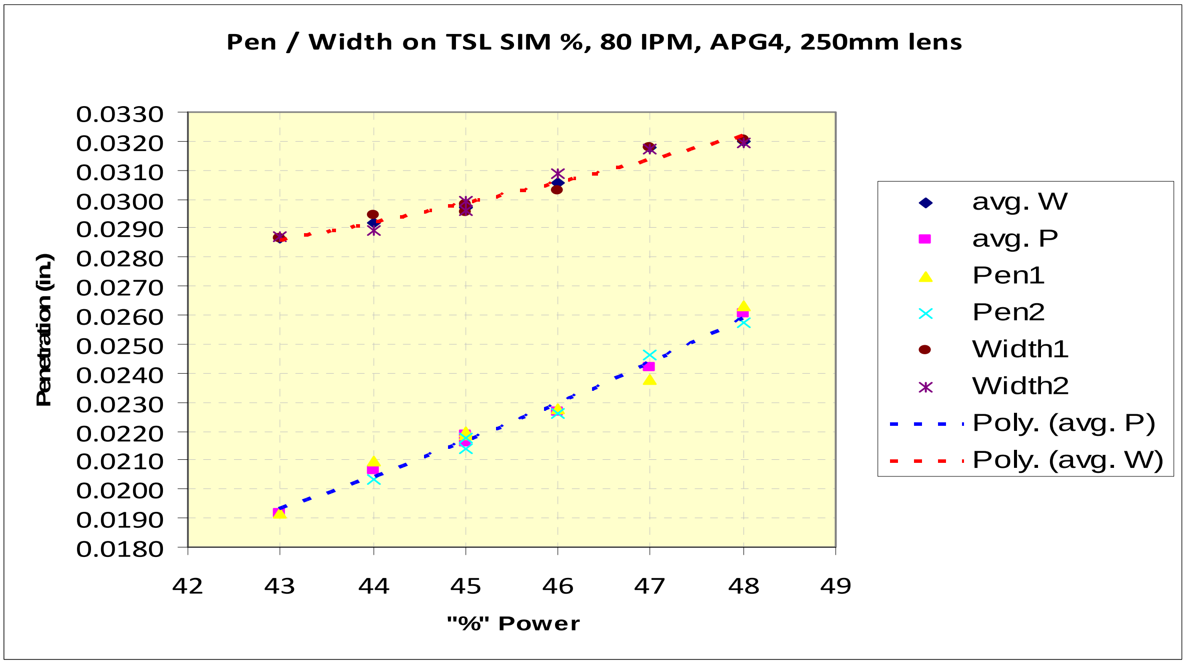

Figure 13. TSL Penetration and Width from Simulated TSL Part with Segmented Welds

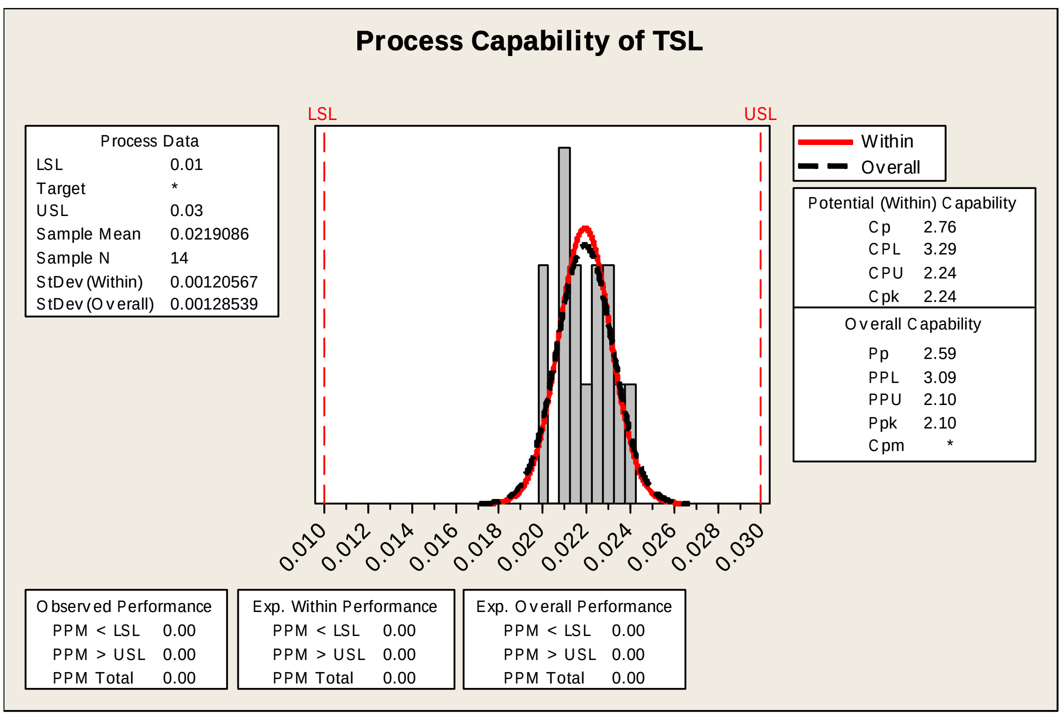

Figure 14. TSL Process Capability of Qualification Welds

Process Capability of Reset Ring Fillets

Two ISL Reset Rings were welded, sectioned and analyzed for process capability resulting in eight fillet and eight butt sections.

The butt sections were included in the Figure 8 “mix”, Process Capability of Butt Joints Combined. Penetration results and process capability of the Reset Ring fillets are shown in Figure 15. The process capability analysis utilized the recently relaxed fillet lower limit of 0.008 inch, ref. ACO 20092603SA.

The Figure 15 histogram uses a unilateral boundary low limit. The nominal fillet “throat” for the group is calculated as 0.0121 inch with a 0.00077 inch standard deviation. Capable process performance is reflected with an overall Ppk of 1.76 sigmas, indicating a mean value that is more than 5-standard deviations away from the lower specification limit.

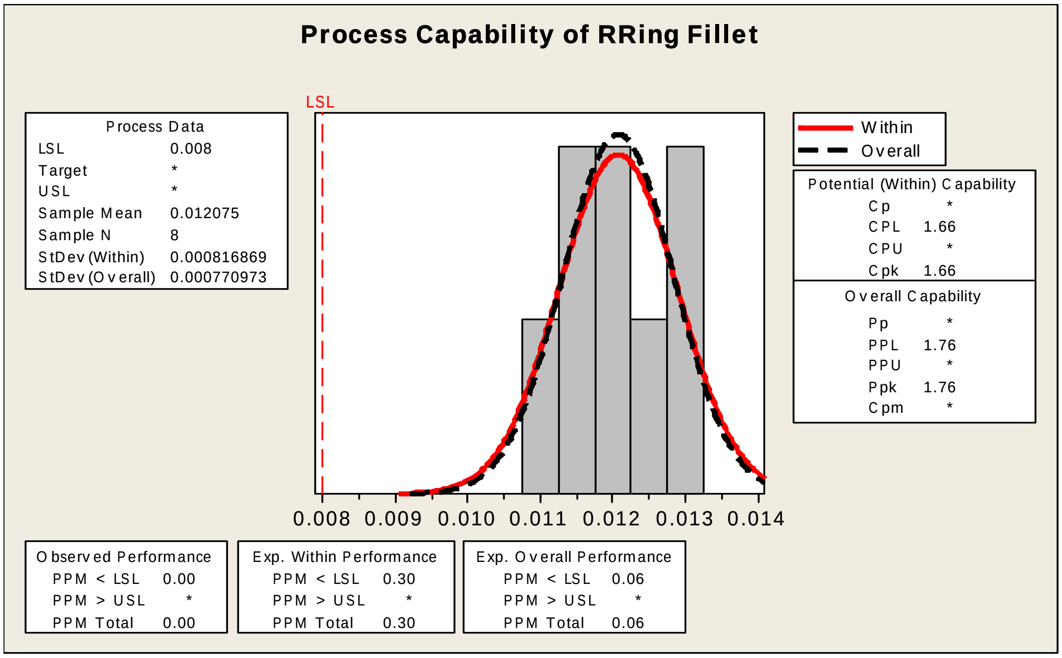

Figure 15. Process Capability of the Reset Rings

Ground Strap and Flatness Cover Weld Parameter Selection

A 2-level, 2-factor, DOE with center point was completed to assess spot welding performance for the Ground Strap and Flatness Cover applications, both of which use the same parameters. The screening work narrowed settings to the below ranges of “%” and “Pulse Time” duration. Single spots are utilized. With the Ground Strap, five minimum overlapping spots are used.

	1 Pulse Time	2 Power %	3 Pen	4 Spot Dia.
1	0.045	22	0.0216	0.0409
2	0.045	30	0.0400	0.0563
3	0.025	22	0.0156	0.0340
4	0.025	30	0.0339	0.0474
5	0.035	26	0.0285	0.0476

Table 2. DOE Matrix with Range of Parameters Used and Captured Response

The above DOE was analyzed and responses charted capturing penetration and spot diameter as function of “%” and pulse time per Figures 16 and 17.

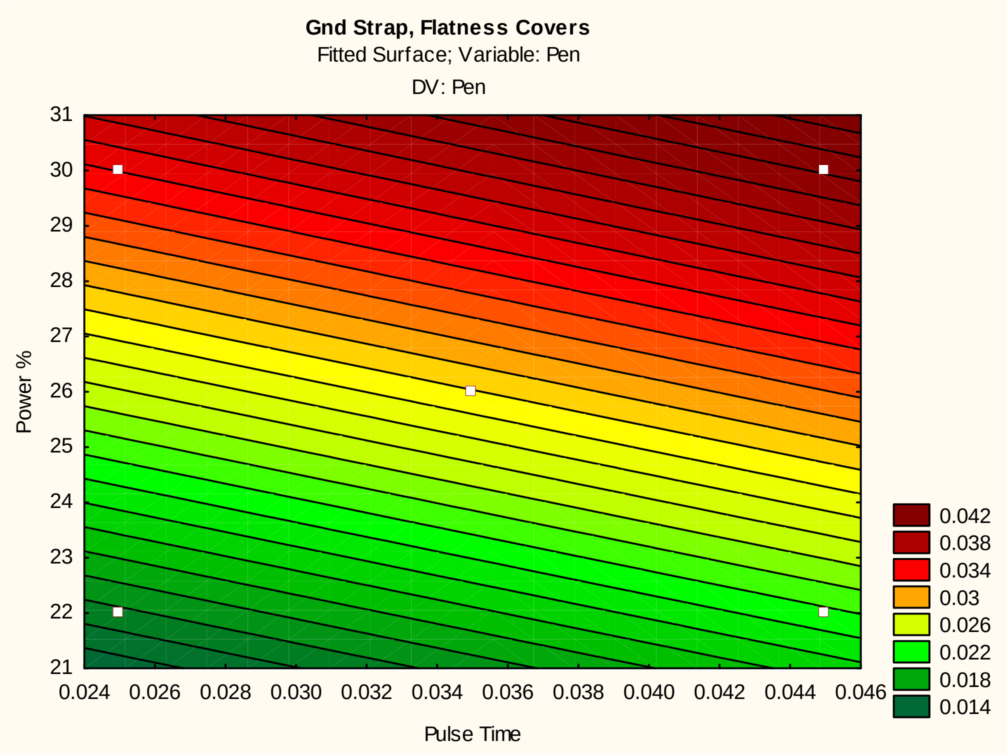

Figure 16. Ground Strap and Flatness Covers Penetration by % and Pulse Duration

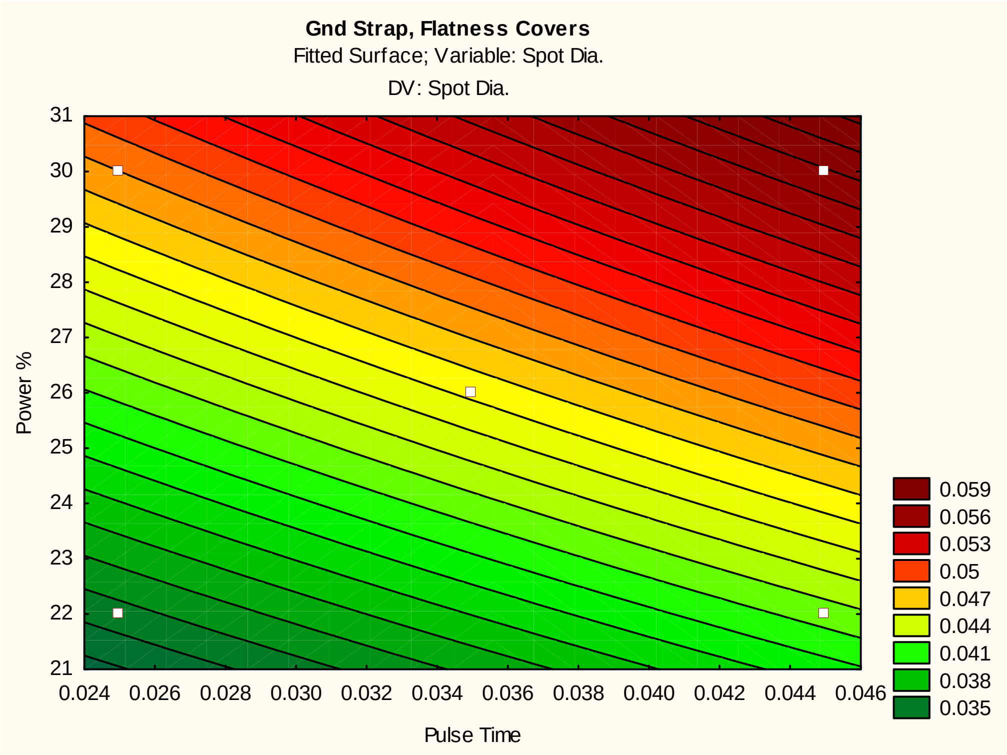

Figure 17. Ground Strap and Flatness Covers Spot Diameter by % and Pulse Duration

From the response, a central parameter was selected with 0.035 sec “on” time and a “%” setting of 26. Pareto analysis of the data indicated “power” as the most significant parameter affecting penetration. Penetration for the nominal setting was measured at 0.028 inch.

Process Capability Summary

Table 3 shows the potential and overall capabilities for the qualification parts for combined geometries of “non-TSL” joints, TSL welds and Reset Ring fillets as produced with the Fiber laser.

PPL, PPU and Ppk values are presented, which are measures of overall process capability, calculated with overall process standard deviation. They measure the distance between the process average and the specification limits, compared to the process spread as follows:

- PPL measures how close the process mean is to the lower specification limit
- PPU measures how close the process mean is to the upper specification limit
- Ppk equals the lesser of PPU and PPL.

The “worst” case Ppk process capability of 4.56 sigma limit is exhibited by the butt joints combined, non-TSL seams, which specify 0.025 inch as nominal. However, with respect to the Lower Specification Limit (LSL), this capability is enhanced due to uncentering, which favors the low limit with a very robust PPL of 8.55-sigmas. Early on it was explained that a larger and more capable process margin to the LSL is highly desirable to optimize process robustness for the /S/ criteria, which is applicable only against the LSL.

The TSL welds exhibit better process capability with Ppk of 2.1 and a sigma level of 6.63 standard deviations. The Reset Ring fillets are likewise robust. They only have a lower limit requirement and display a sigma level of 5.28.

These figures predict the expected performances in terms of potential fallout from the process with the worst case being 2.72 PPM. This is a significant improvement over historical PPM for the YAGs, which originally exhibited 275.18 PPM for combined butt joints[11].

Non-TSL Butt Seams				TSL Weld				Reset Ring Fillet Weld			
Overall Capability		Sigma Level	Expected Performance	Overall Capability		Sigma Level	Expected Performance	Overall Capability		Sigma Level	Expected Performance
PPL	2.85	8.55		PPL	3.09	9.27		PPL	1.76	5.28	
PPU	1.52	4.56		PPU	2.1	6.3		PPU	*	n/a	
Ppk	1.52	4.56		Ppk	2.1	6.3		Ppk	1.76	5.28	
PPM < LSL			0	PPM < LSL			0	PPM < LSL			0.06
PPM > USL			2.72	PPM > USL			0	PPM > USL			*
PPM Total			2.72	PPM Total			0	PPM Total			0.06

Table 3. Fiber Laser Process Capability and Expected Performance

Secondary Attachment Pins Parameter Selection

A screening DOE was initially completed to verify welding conditions at multiple “%” power and pulse time settings. Pulsing with the fiber is done in the CW mode by temporally switching the cavity for the programmed pulse duration.

Welds were made using Table 4, indicating the range of parameters. Metallography of welded pins indicated excessive base penetration above the 30% power value so the initial screen was discarded in favor of using only the lower power selection of 25%, which produced optimum appearance and the least spatter.

I.D	"%"	Pulse Time (sec)	IPG (W)	Ophir (W)	Comments
1	35	0.035	816	625	spatter
2	25	0.035	545	417	best
3	35	0.025	816	625	spatter
4	25	0.025	545	417	best
5	30	0.030	679	521	spatter

Table 4. Pins Screening DOE Matrix

A second excursion of parameters was made based on the appearance of the first screen. The second group held power constant at 25% with "on" times shifted between 0.025 sec and 0.040 sec to achieve the desired visual appearance with good surface coverage and pin-to-TSL "bridging". The high value of .040 sec was selected based on nugget size and compliance to the penetration criteria for fillet and base numbers. Also, weld size was verified for robustness to accommodate large pin-to-housing gaps. Many of the samples exhibited significant gaps of up to 0.008 inch from misalignment of the mating holes forcing use of small pin diameters.

Results are per the below, Table 5. All values are in compliance to SS1A4542.

I.D	"%"	Pulse Time (sec)	Ophir (W)	"Throat"	Base	Comments
1	25	0.025	417	0.0172	fused	
2	25	0.030	417	0.0182	fused	
3	25	0.035	417	0.0160	fused	
4	25	0.040	417	0.0171	fused	
5	25	0.040	417	0.0148	fused	
6	25	0.040	417	0.0123	fused	
7	25	0.040	417	0.0164	fused	
8	25	0.040	417	0.0170	fused	
9	25	0.040	417	0.0150	fused	
10	25	0.040	417	0.0127	fused	Oxidized
11	25	0.040	417	0.0155	fused	
avg.				0.0151		
std. dev.(4 - 11)				0.0018		

Table 5. Final Value Range Selection

Positioning of the pins was selected to allow a gap between two groupings of overlapping spot welds, approximately 0.045-inch in diameter each. Each grouping of spots contains seven spot welds spaced 0.007" apart and positioned along the periphery of the pin's head and central to the thickness (0.020-inch), in accordance with the below graphic:

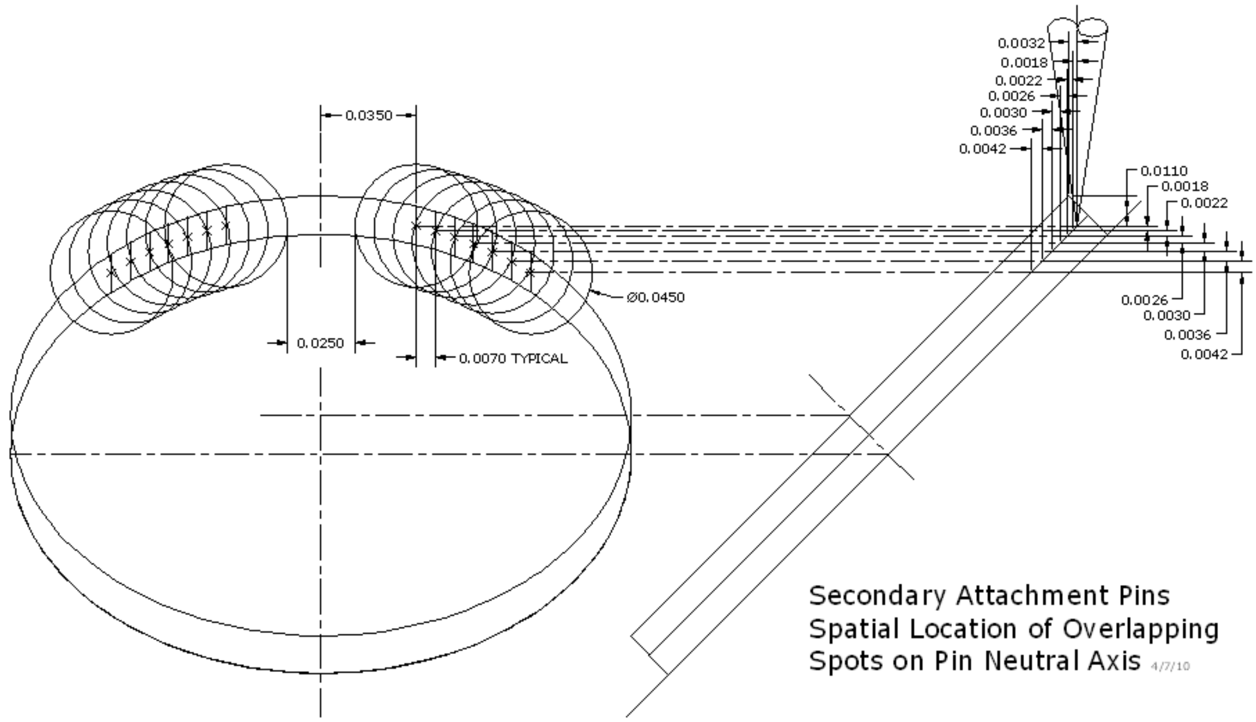

Figure 18. Placement of Spot Welds on Secondary Attachment Pins

Process Capability of Secondary Attachment Pins

Values from table 5 were analyzed and were confirmed to be normally distributed based on the Anderson-Darling test. Process capability was subsequently calculated using a Lower Specification Limit (LSL) of 0.010-inch with results per the below Figure 19. The expected Overall Performance shown is 1125.91 PPM (PPL, 1.03), which equates to about 0.1% potential fallout from the process. This application reflects the least capable process for the welds shown in this report or a process with slightly over 3-sigma standard deviations from the mean. An LSL of 0.008 inch would increase the process capability, PPL to 1.37, or over 4-sigma with an improved expected overall performance of 18.89 PPM.

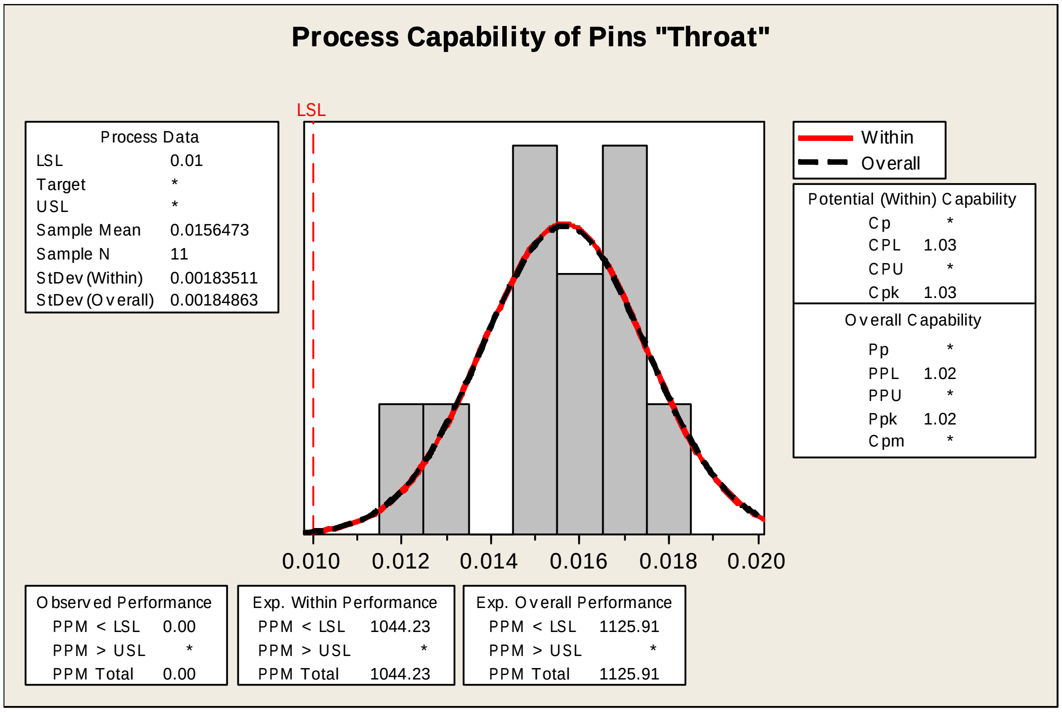

Figure 19. Process Capability of Secondary Attachment Pins

<u>ISL Thermal Testing</u>

A thermocoupled (TC) ISL was used to compare the YAG-to-Fiber thermal response. Previous data from the existing YAG lasers existed from this weld and could be used for comparison. TCs were placed at both long legs and one short leg of the ISL located approximately 0.080 inch from the weld and behind the ISL standing welded edge. Peak temperatures recorded from "Home" position and moving counter clockwise for TC#1, TC#2 and TC#3 indicated 113, 180 and 257°C respectively with an overall average of 183.7 °C for the Fiber vs. 208°C for the existing YAGs based on previously recorded temperature data. See Figure 15, below.

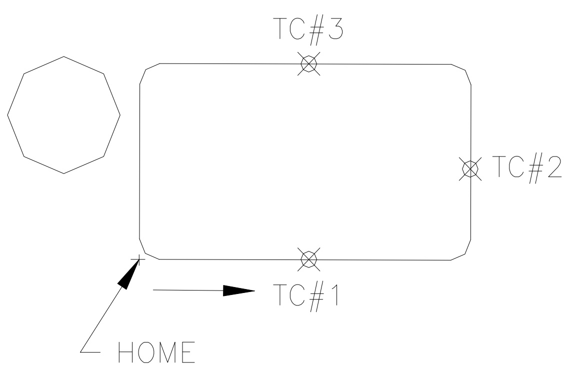

Figure 20. Orientation of Thermocouples and Weld Direction from "Home"

Recommendations

- Eliminate partial-penetration "square-groove" designs that require costly and strict tolerancing, flushness and edge breaks and which place the burden of penetration control on the equipment and the process. Because of limitations of the partial penetration scheme, often the dimensional definition and fit up of the parts themselves are not conducive to robust process capability.

- Eliminate very tight tolerances for partial-penetration joints (as above) in favor of full penetration, backed-up joints with flange thicknesses that fit in counterbored “pockets” whose depths define the needed weld penetration.
- Unless critical upper–end boundary conditions exist for the product, call out only unilateral limits that allow the flexibility to select machine parameters that are robust to the minimum penetration limit. Bilateral dimensioning forces selection of centered machine parameters that may not be optimum for manufacturability.
- Flange thicknesses of “lap” welds should be sufficiently robust to accommodate the “throat” criteria. The throat requirement should never exceed 50% of the flange thickness. For typical Firing Set sizing of welds, the flange thickness should be kept to 0.020 inch maximum.
- Product tolerancing should allow at least 6-sigma (standard deviation limits) to either side of the mean value of the requirement based on the standard deviation of the specific equipment capability.
- Provide “product-based” criteria based on the functional requirement of each weld instead of “process-based” limits that reflect the equipment capability.

Accomplishments

- First-time use of a fiber laser for WR production of Firing Set and AF&Fs at the KCP
- Penetration and dimensional criteria were met, which were compliant to SS1A4542 requirements
- Commissioning of equipment within a compressed time frame
- Characterization of temperature profiles for the ISL weld, indicating similar response with the existing YAG weld process

Conclusion

Based on the metallography, dimensional and visual results presented, CE214603, fiber laser, complies with the specifics of SS1A4542 for Firing Set production welding qualification.

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9 SS1A4542, Welding Requirements, MC4702 (U), Issue P, ACO20092603SA, C. F. Briner, SNLA 2625, A. Young, KC831, November 2009.

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11 J. Samayoa, “Development of a Welding Capability for a Firing Set”, KCP-613-8198, Honeywell Federal Manufacturing & Technologies, September 2006.

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Appendix “A”

Fiber Laser Qualification Results

Fiber Laser Weld Qualification Results

Group	Name / Section I.D.	Part or Sample	LTR#	Weld Penetration Butt Joint	Weld Penetration OOF	Weld Penetration Offset	Fillet Penetration Throat	Fillet Penetration Base	Width / Spot Dia.	Group Avg.	Date Welded
n/a	S/P	Snap Plate		0.0272	n/a	n/a	n/a	n/a			
n/a	S/P	Snap Plate		0.0257	n/a	n/a	n/a	n/a		0.0267	
n/a	S/P	Snap Plate		0.0277	n/a	n/a	n/a	n/a			
n/a	S/P	Snap Plate		0.0283	n/a	n/a	n/a	n/a			
1	TSL1-1A	Part (hsg) / Part (TSL)	60859	0.0242	0.0000	n/a	n/a	n/a	0.0305		2/9/2010
1	TSL1-2A	Part (hsg) / Part (TSL)	60859	0.0224	0.0000	n/a	n/a	n/a	n/a		2/9/2010
1	TSL1-1B	Part (hsg) / Part (TSL)	60859	0.0198	0.0054	n/a	n/a	n/a	0.0302		2/9/2010
1	TSL1-1C	Part (hsg) / Part (TSL)	60859	0.0222	0.0030	n/a	n/a	n/a	0.0303		2/9/2010
1	TSL1-2C	Part (hsg) / Part (TSL)	60859	0.0215	0.0040	n/a	n/a	n/a	n/a		2/9/2010
1	TSL1-1D	Part (hsg) / Part (TSL)	60859	0.0216	0.0030	n/a	n/a	n/a	0.0311		2/9/2010
1	TSL1-1E	Part (hsg) / Part (TSL)	60859	0.0212	0.0033	n/a	n/a	n/a	0.0310	0.0219	2/9/2010
1	TSL2-1A	Part (hsg) / Part (TSL)	60859	0.0209	0.0026	n/a	n/a	n/a	0.0310		2/10/2010
1	TSL2-2A	Part (hsg) / Part (TSL)	60859	0.0201	0.0025	n/a	n/a	n/a	n/a		2/10/2010
1	TSL2-1B	Part (hsg) / Part (TSL)	60859	0.0230	0.0025	n/a	n/a	n/a	0.0302		2/10/2010
1	TSL2-1C	Part (hsg) / Part (TSL)	60859	0.0208	0.0025	n/a	n/a	n/a	0.0296		2/10/2010
1	TSL2-2C	Part (hsg) / Part (TSL)	60859	0.0228	0.0030	n/a	n/a	n/a	n/a		2/10/2010
1	TSL2-1D	Part (hsg) / Part (TSL)	60859	0.0235	0.0016	n/a	n/a	n/a	0.0299		2/10/2010
1	TSL2-1E	Part (hsg) / Part (TSL)	60859	0.0227	0.0010	n/a	n/a	n/a	0.0300		2/10/2010
2	J7 1	Part (hsg) / Part (J7)	60853	0.0252	0.0050	n/a	n/a	n/a	n/a		
2	J7 2	Part (hsg) / Part (J7)	60853	0.0275	0.0010	n/a	n/a	n/a	n/a		
2	J7 3	Part (hsg) / Part (J7)	60853	0.0275	0.0030	n/a	n/a	n/a	n/a		
2	J7 4	Part (hsg) / Part (J7)	60853	0.0272	0.0020	n/a	n/a	n/a	n/a		
2	J8 1	Part (hsg) / Part (J8)	60853	0.0267	0.0000	n/a	n/a	n/a	n/a		
2	J8 2	Part (hsg) / Part (J8)	60853	0.0285	0.0000	n/a	n/a	n/a	n/a	0.0275	
2	J8 3	Part (hsg) / Part (J8)	60853	0.0291	0.0020	n/a	n/a	n/a	n/a		
2	J8 4	Part (hsg) / Part (J8)	60853	0.0285	0.0050	n/a	n/a	n/a	n/a		
2	J3 -1	Part (hsg) / Part (J3)	60853	0.0265	0.0000	n/a	n/a	n/a	n/a		2/10/2010
2	J3 -2	Part (hsg) / Part (J3)	60853	0.0269	0.0000	n/a	n/a	n/a	n/a		2/10/2010
2	J3 -3	Part (hsg) / Part (J3)	60853	0.0270	0.0000	n/a	n/a	n/a	n/a		2/10/2010
2	J3 -4	Part (hsg) / Part (J3)	60853	0.0264	0.0000	n/a	n/a	n/a	n/a		2/10/2010
3	ISL Reset Ring, butt 1-1	Part (hsg) / Part (ISL)	60853	0.0278	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 1-2	Part (hsg) / Part (ISL)	60853	0.0307	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 1-3	Part (hsg) / Part (ISL)	60853	0.0281	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 1-4	Part (hsg) / Part (ISL)	60853	0.0286	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 2-1	Part (hsg) / Part (ISL)	60853	0.0286	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 2-2	Part (hsg) / Part (ISL)	60853	0.0283	0.0000	n/a	n/a	n/a	n/a	0.0284	
3	ISL Reset Ring, butt 2-3	Part (hsg) / Part (ISL)	60853	0.0302	0.0000	n/a	n/a	n/a	n/a		
3	ISL Reset Ring, butt 2-4	Part (hsg) / Part (ISL)	60853	0.0289	0.0000	n/a	n/a	n/a	n/a		
3	LA 1	Part (hsg) / SIM (LA)	60853	0.0305	0.0000	n/a	n/a	n/a	n/a		
3	LA 2	Part (hsg) / SIM (LA)	60853	0.0267	0.0050	n/a	n/a	n/a	n/a		
3	LA 3	Part (hsg) / SIM (LA)	60853	0.0277	0.0030	n/a	n/a	n/a	n/a		
3	LA 4	Part (hsg) / SIM (LA)	60853	0.0248	0.0060	0.0040	n/a	n/a	n/a		
4	ISL Reset Ring, fillet 1-1	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0113	fully fused	n/a		
4	ISL Reset Ring, fillet 1-2	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0119	fully fused	n/a		
4	ISL Reset Ring, fillet 1-3	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0116	fully fused	n/a		
4	ISL Reset Ring, fillet 1-4	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0132	fully fused	n/a		
4	ISL Reset Ring, fillet 2-1	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0126	fully fused	n/a	0.0121	
4	ISL Reset Ring, fillet 2-2	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0119	fully fused	n/a		
4	ISL Reset Ring, fillet 2-3	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0111	fully fused	n/a		
4	ISL Reset Ring, fillet 2-4	Part (VAR ring) / Part (ISL)	60853	n/a	n/a	n/a	0.0130	fully fused	n/a		
5	Gnd Strap	SIM (strap) / SIM (hsg)	60800	n/a	n/a	n/a	0.0103	0.028	0.0476	0.0104	
5	Gnd Strap	SIM (strap) / SIM (hsg)	60800	n/a	n/a	n/a	0.0105	0.031	0.0480		
6	2nd Attach Pins 1-1	SIM (hsg) / Part (pin)	60853	n/a	n/a	n/a	0.0148	fully fused	n/a	0.0136	
6	2nd Attach Pins 1-2	SIM (hsg) / Part (pin)	60853	n/a	n/a	n/a	0.0123	fully fused	n/a		

Appendix "B"

WPQR Settings for Validation

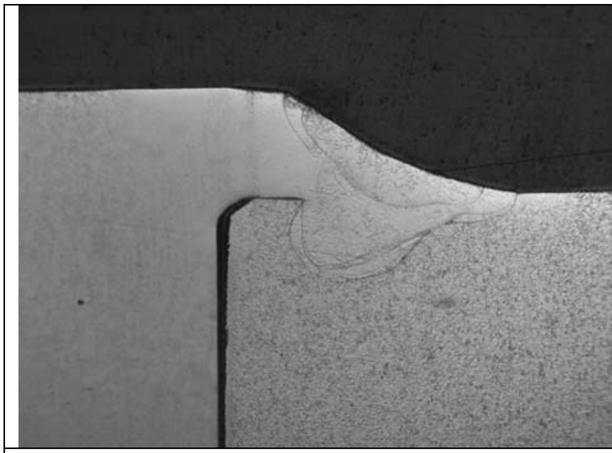
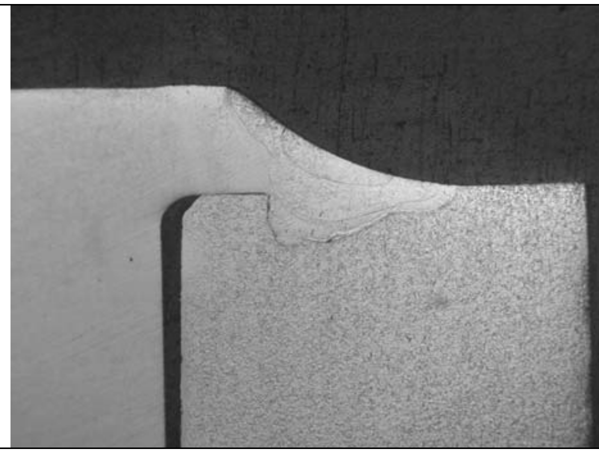
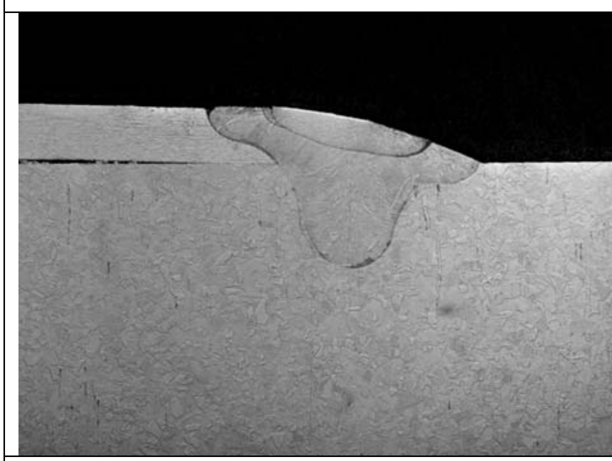
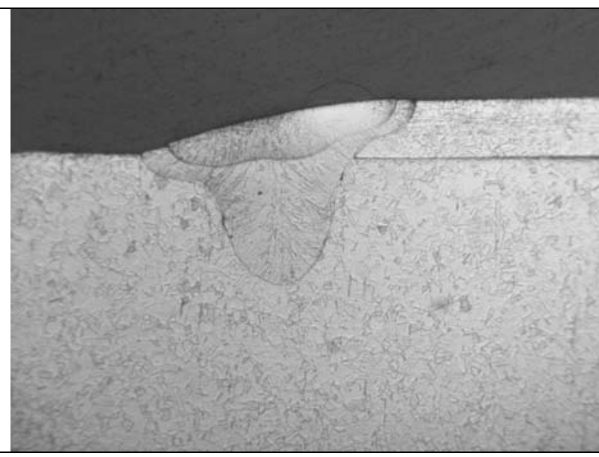
WPS NOMINAL SETTINGS FOR WPQR VALIDATION

GROUP#	WPS#	WELD		SEAM	TACK	NOM. %	NOMINAL POWER & RANGE	WELD SPEED	TACK TIME (SEC)	ARGON GAS, Chrome ball, Mat 605 COAX FLOW	SIDE 2 FLOW	SIDE 1 FLOW
2	1A1900-LBW1C	J1		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
2	1A1900-LBW2C	J2		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
2 ✓	1A1099-LBW3C	J3		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
2	1A1900-LBW4C	J4, J5	J4, J5, USE SAME SCHEDULE	X		48	375+20/-20 (SINE)	80	N/A	120	120	120
2 ✓	1A1099-LBW6C	J6, J7, J8	J6, J7, J8, USE SAME SCHEDULE	X		48	375+20/-20 (SINE)	80	N/A	120	120	120
6 ✓	1A1099-LBW9C	2nd ATTACHMENT PINS			X	25	375+20/-20 (SINE)	80	0.040	120	120	120
1 ✓	1A1099-LBW10C	TRAJECTORY STRONG LINK (TSL)		X		45	345+20/-20 (SINE)	80	N/A	120	120	120
3	1A1099-LBW11C	INTENT STRONG LINK (ISL)		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
4 ✓	1A1099-LBW12C	RESET RING, ISL (FILLET)		X		48	375+20/-20 (SINE)	70	N/A	120	120	120
3 ✓	1A1099-LBW13C	RESET RING, ISL (BUTT)		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
4	1A1900-LBW14C	RESET RING, TSL (FILLET)		X		48	375+20/-20 (SINE)	70	N/A	120	120	120
3	1A1900-LBW15C	RESET RING, TSL (BUTT)		X		48	375+20/-20 (SINE)	80	N/A	120	120	120
5 ✓	1A1900-LBW16C	CDU GROUND STRAP						80	0.040	120	120	120
5	1A1900-LBW16C	FLATNESS COVER ISL	CDU GND. STRAP, ISL/TSL FLAT COVERS USE THE SAME SCHEDULE		X	25	420+25/-0 (CW)	80	N/A	120	120	120
5	1A1900-LBW16C	FLATNESS COVER TSL						80	N/A	120	120	120
3	1A1900-LBW17C	REGION 2 COVER		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
3	1A1900-LBW18C	FWD COVER		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
3	1A1900-LBW18CT	FWD COVER (TILT)		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
3	1A1900-LBW19C	AFT COVER		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
3	1A1900-LBW21C	LAUNCH ACCELEROMETER (LA)		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
3	1A1900-LBW22C	PURGE TUBE (PT)		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
n/a	1A1099-LBW26C	MANUAL TACK WELDING	CDU GND. STUD, MANUAL TACK USE THE SAME SCHEDULE		X	25	420+25/-0 (CW)	80	0.020	120	120	120
n/a	1A1099-LBW28C	TSL ALIGNMENT PASS		N/A	N/A	N/A	375+25/-10 (SINE)	80	N/A	N/A	N/A	N/A
n/a	1A1099-LBW30C	"SNAP-PLATE" FUNCTIONAL		X		48	375+25/-10 (SINE)	80	N/A	120	120	120
8	1A1078-LBW1C	CDU GROUND STUD*	SAME AS 1A1099-LBW26C	*	*	*	*	*	*	*	*	*
✓	indicates parts welc	*not qualified										

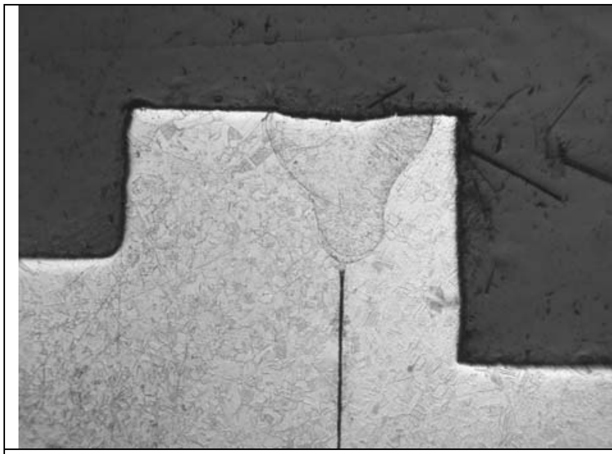
Appendix "C"

Weld Metallography

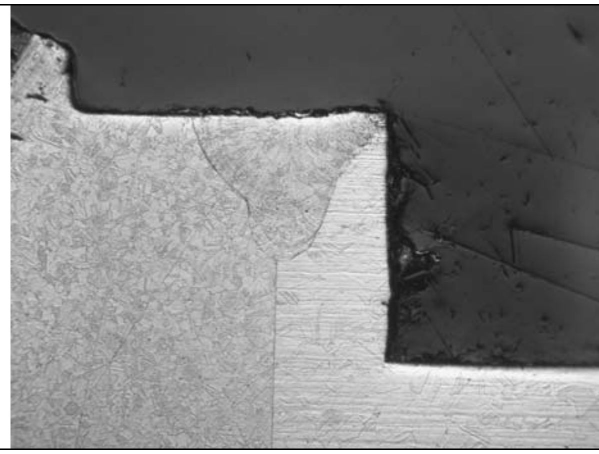
Secondary Attachment Pins and Ground Strap / Flatness Covers

	
Secondary Attachment Pins, Fillet = .0148" **Base Pen = Fully fused**	**Secondary Attachment Pins, Fillet = .0123"** **Base Pen = Fully fused**
	
Gnd Strap / Flat. Covers; Fillet = 0.0103" **Base Pen=.028"**	**Gnd Strap / Flat. Covers; Fillet = 0.0105"** **Base Pen=.031"**

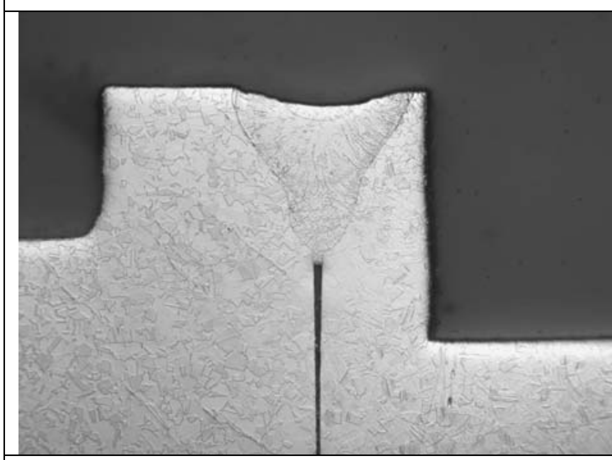
J3 Connector



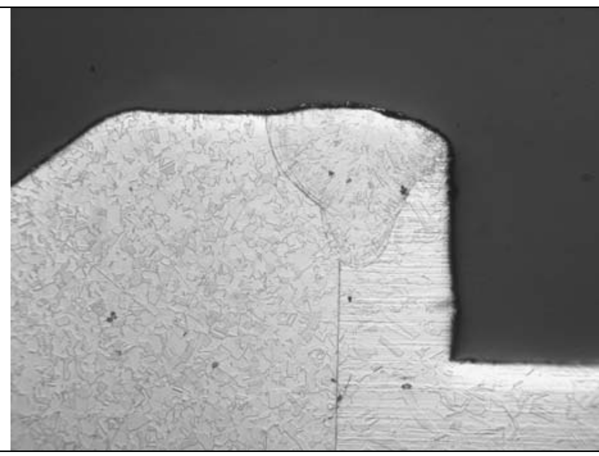
J3 Pen = 0.0265”



J3 Pen = 0.0269”

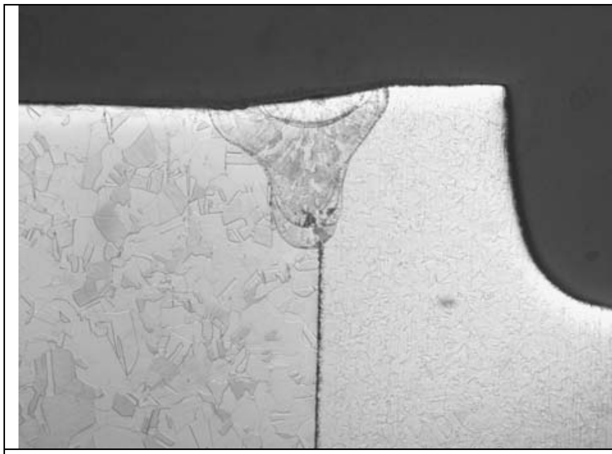


J3 Pen = 0.0270”



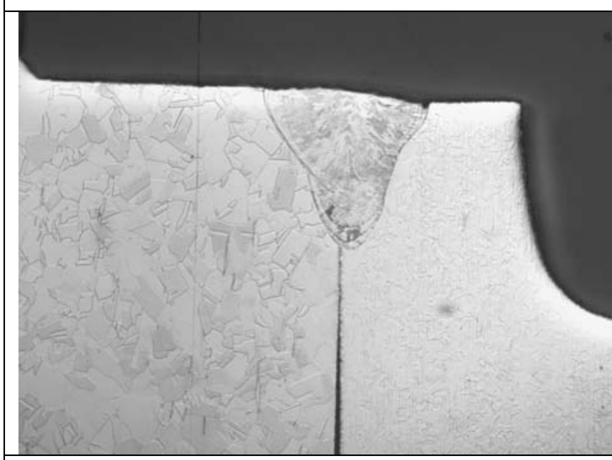
J3 Pen = 0.0264”

J7 Connector

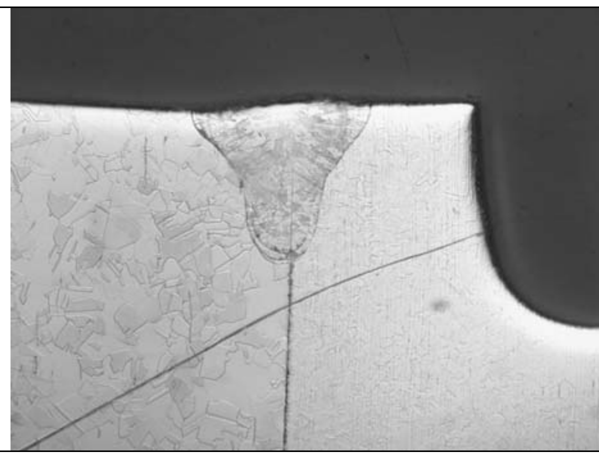


J7-1 Pen = 0.0252”

J7-2 Pen = 0.0275”

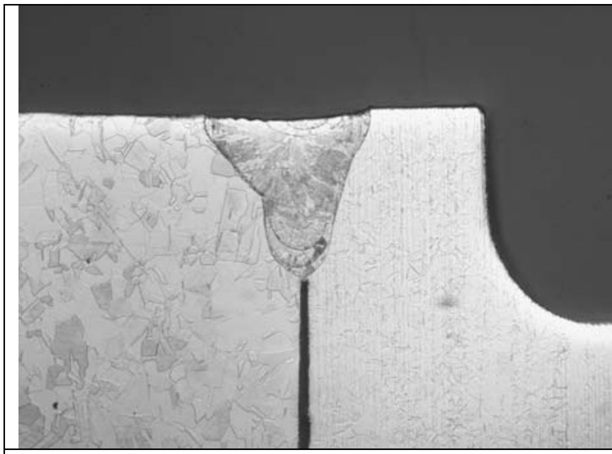
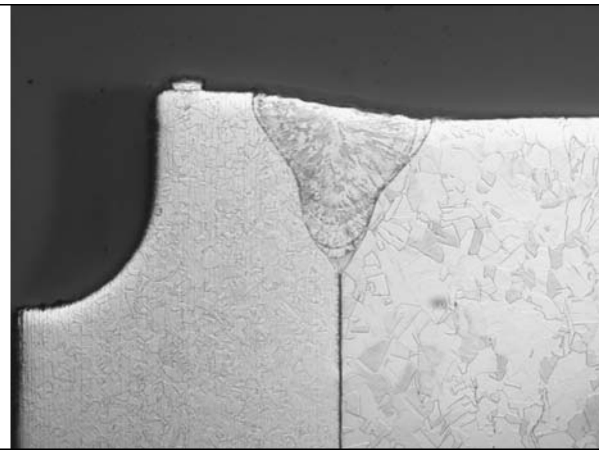
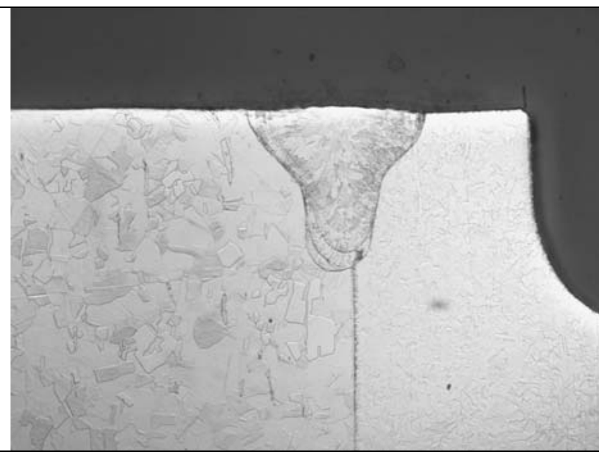


J7-3 Pen = 0.0275”



J7-4 Pen = 0.0272”

J8 Connector

	
J8-1 Pen = 0.0267"	**J8-2 Pen = 0.0285"**
	
J8-3 Pen = 0.0291"	**J8-4 Pen = 0.0285"**

Launch Accelerometer (LA)

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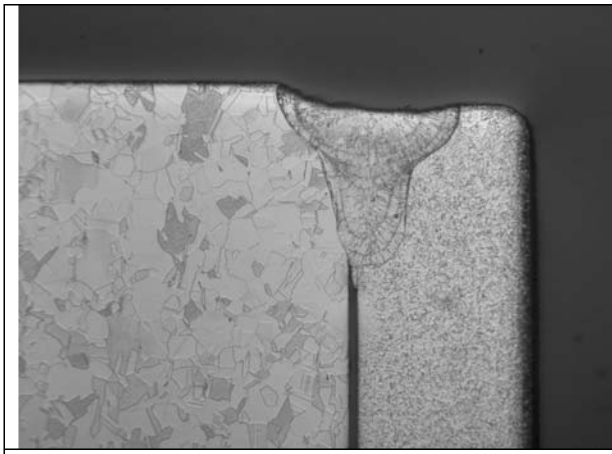
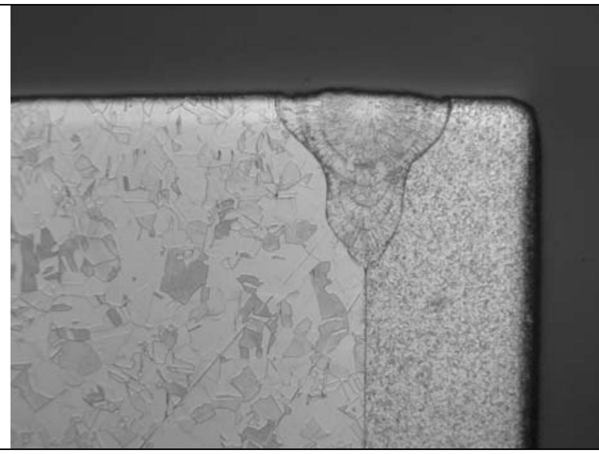
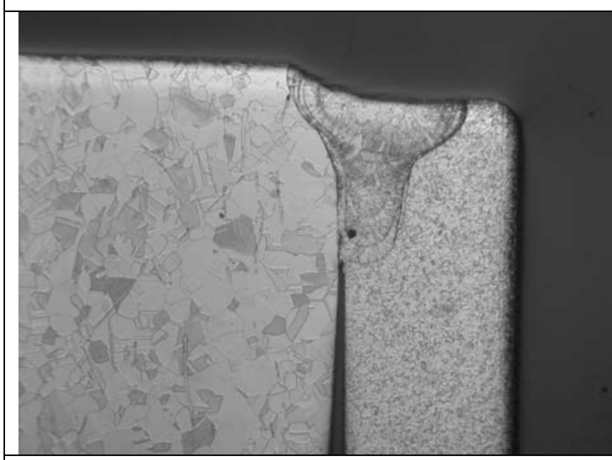
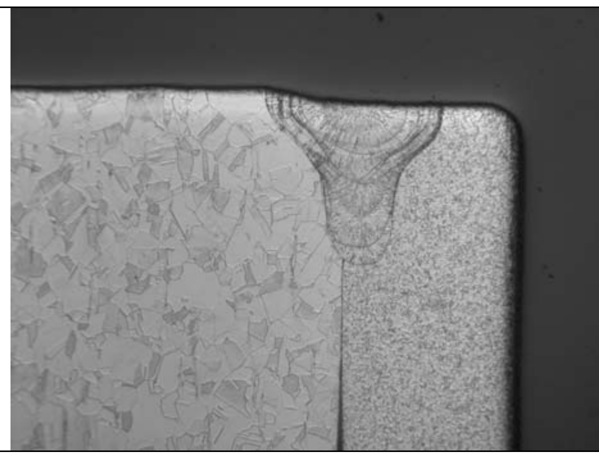
<tr><td></td><td></td></tr>
<tr><td>LA1 Pen = 0.0267”</td><td>LA2 Pen = 0.0305”</td></tr>
<tr><td></td><td></td></tr>
<tr><td>LA3 Pen = 0.0248”</td><td>LA4 Pen = 0.0277”</td></tr>
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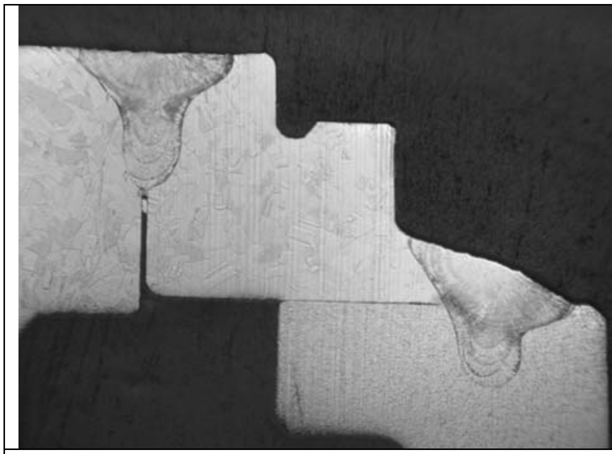
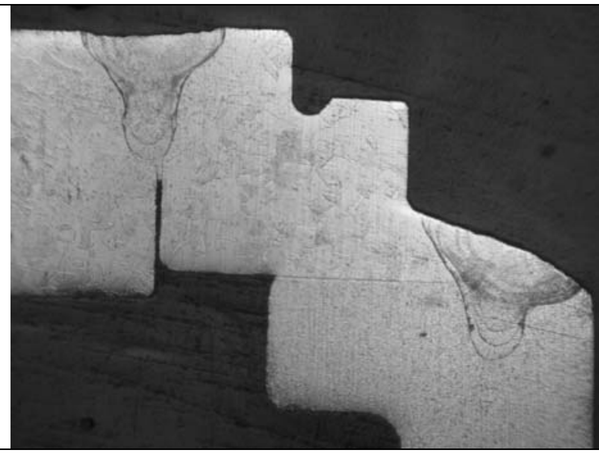
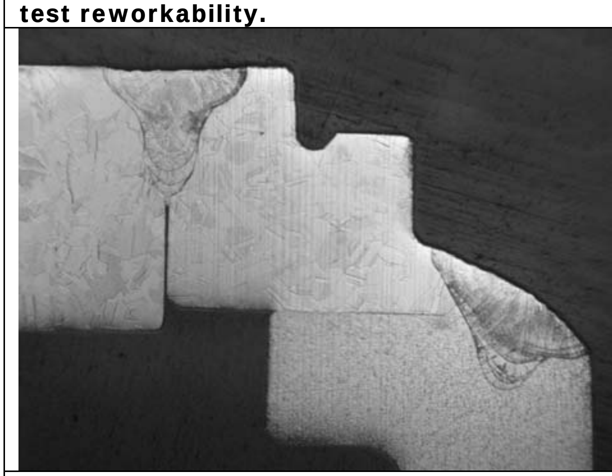
ISL Reset Ring #1



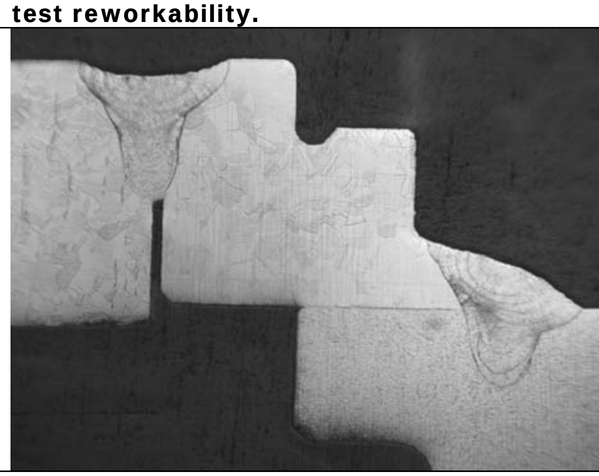
RRing1-1 Pen= 0.0278” Fillet = 0.0113” Base is fully fused. Fillets were rewelded to test reworkability.



RRing1-2 Pen= 0.0307” Fillet = 0.0119” Base is fully fused. Fillets were rewelded to test reworkability.

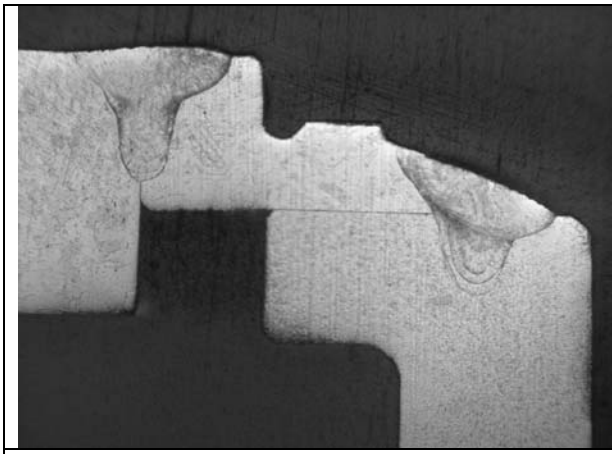
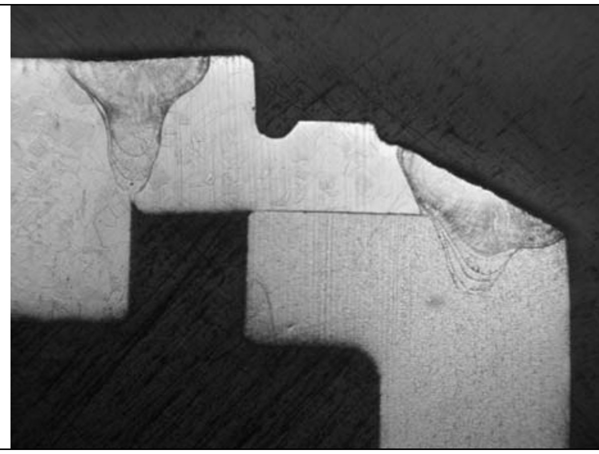
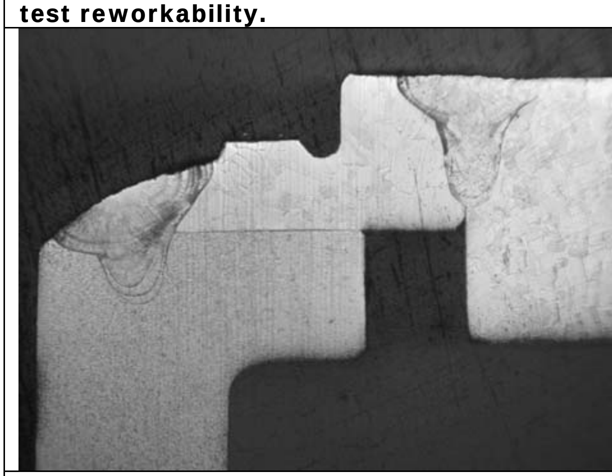
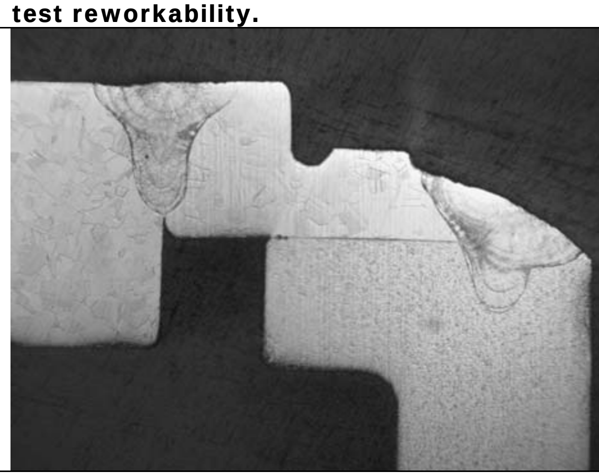


RRing1-1 Pen= 0.0281” Fillet = 0.0116” Base is fully fused. Fillets were rewelded to test reworkability.

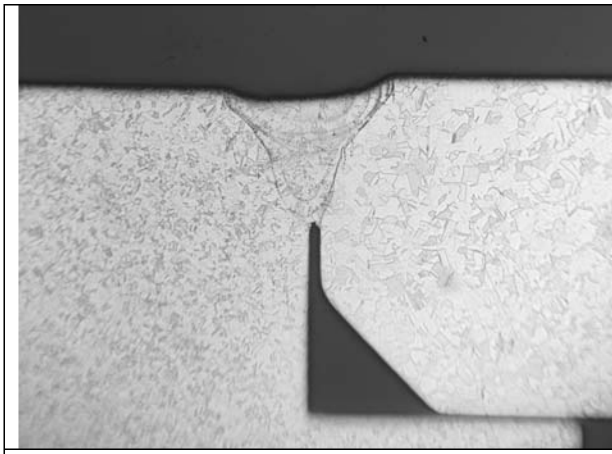


RRing1-1 Pen= 0.0286” Fillet = 0.0132” Base is fully fused. Fillets were rewelded to test reworkability.

ISL Reset Ring #2

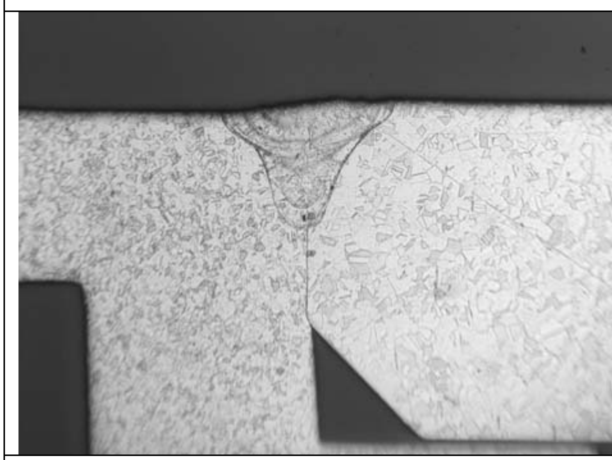
	
RRing2-1 Pen= 0.0286" Fillet = 0.0126" Base is fully fused. Fillets were rewelded to test reworkability.	**RRing2-2 Pen= 0.0283" Fillet = 0.0119" Base is fully fused. Fillets were rewelded to test reworkability.**
	
RRing2-3 Pen= 0.0302" Fillet = 0.0111" Base is fully fused. Fillets were rewelded to test reworkability.	**RRing2-4 Pen= 0.0289" Fillet = 0.0130" Base is fully fused. Fillets were rewelded to test reworkability.**

TSL

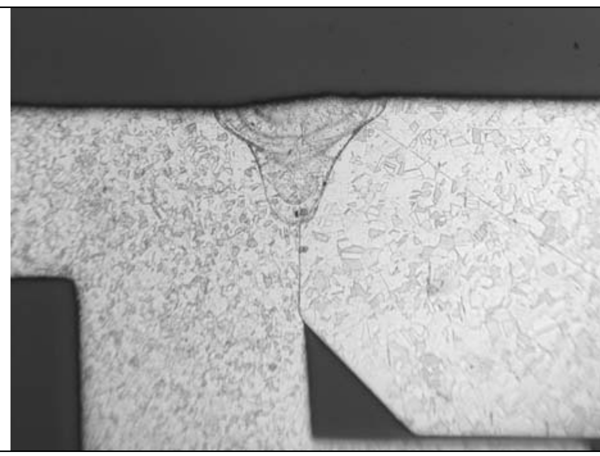


TSL1, 1A Pen = 0.0242”

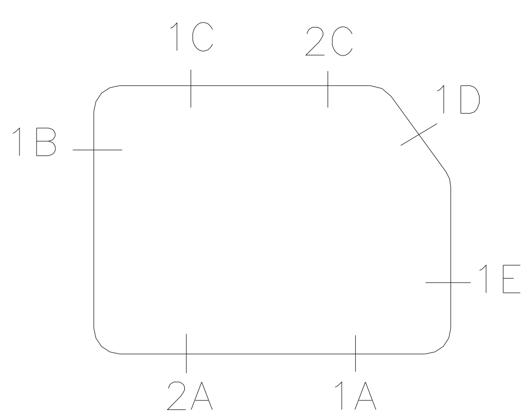
TSL1, 2A Pen = 0.0224”

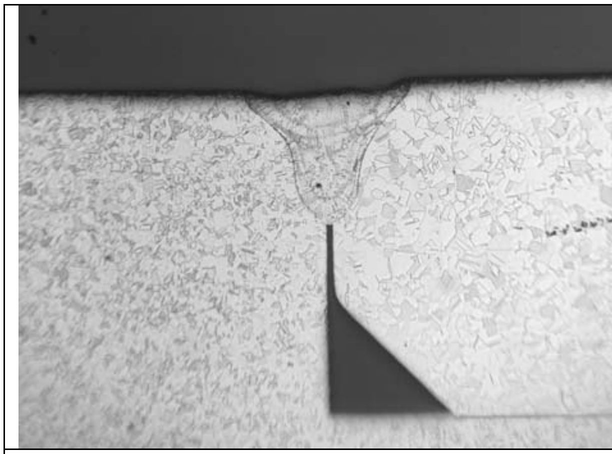


TSL1, 1B Pen = 0.0198”

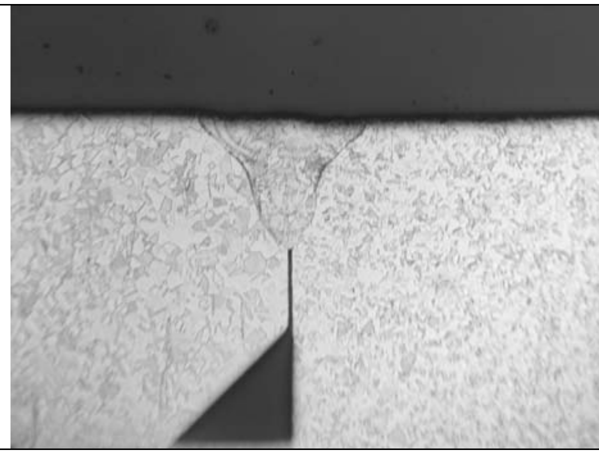


TSL1, 1C Pen = 0.0222”

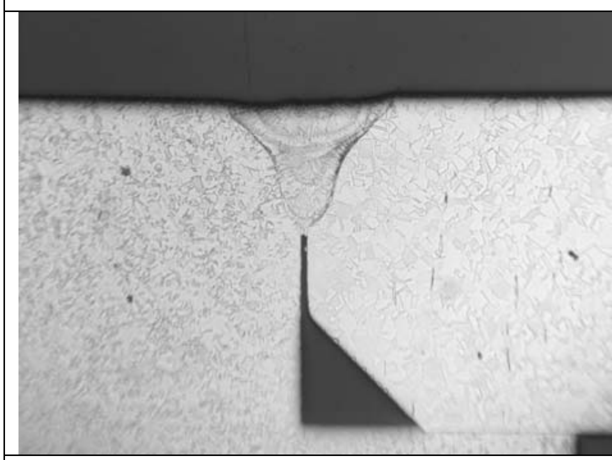




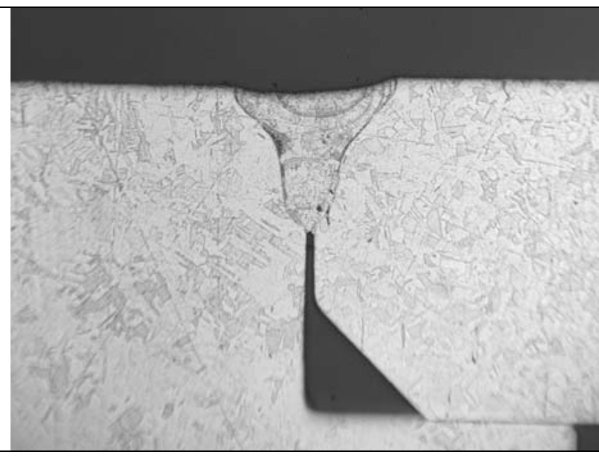
TSL1, 2C Pen = 0.0215”



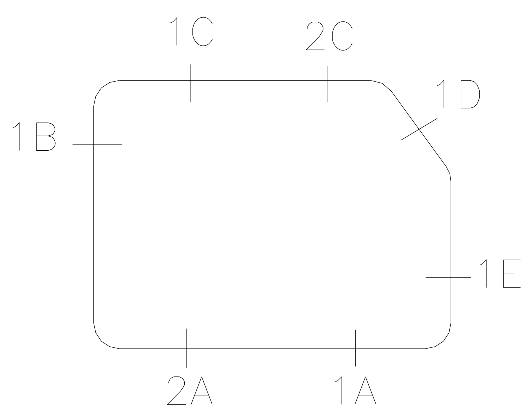
TSL1, 1D Pen = 0.0216”

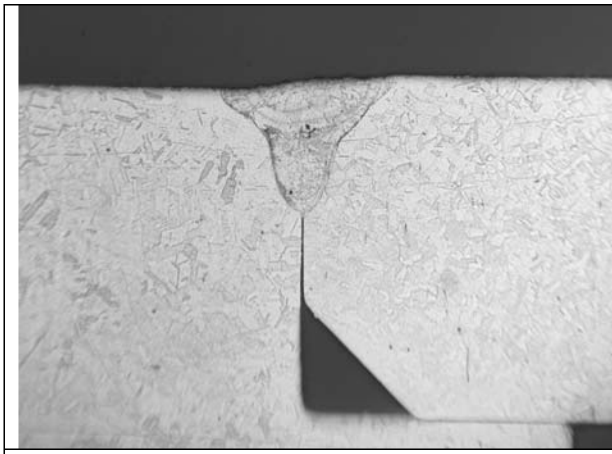
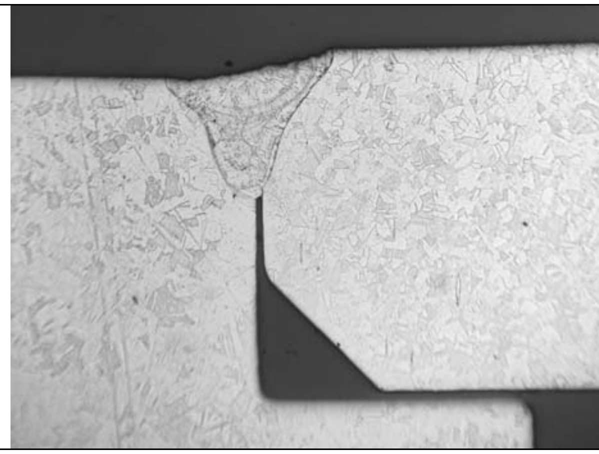
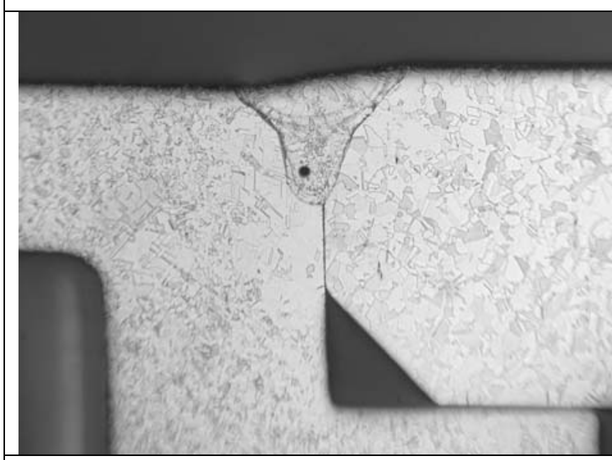
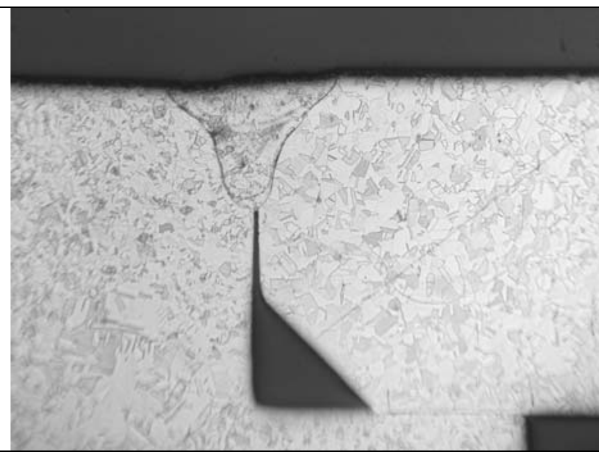


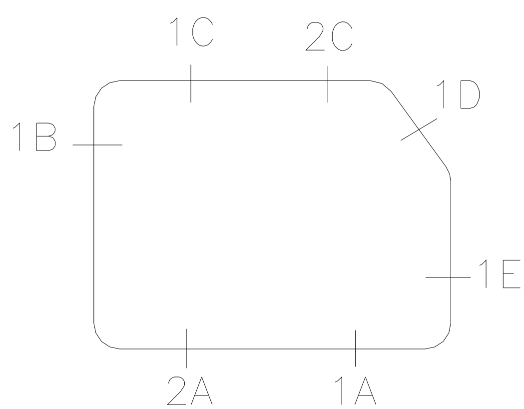
TSL1, 1E Pen = 0.0212”



TSL2, 1A Pen = 0.0209”



	
TSL2, 2A Pen = 0.0201”	**TSL2, 1B Pen = 0.0230”**
	
TSL2, 1C Pen = 0.0208”	**TSL2, 2C Pen = 0.0228”**



	
TSL2, 1D Pen = 0.0235"	**TSL2, 1E Pen = 0.0227"**