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Laser Engineered Net Shaping™ (LENS®) for the Repair and Modification of NWC Metal Components

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Abstract

Laser Engineered Net Shaping™ (LENS®) is a layer additive manufacturing process that creates fully dense metal components using a laser, metal powder, and a computer solid model. This process has previously been utilized in research settings to create metal components and new material alloys. The "Qualification of LENS for the Repair and Modification of Metal NWC Components" project team has completed a Technology Investment project to investigate the use of LENS for repair of high rigor components. The team submitted components from four NWC sites for repair or modification using the LENS process. These components were then evaluated for their compatibility to high rigor weapons applications. The repairs included hole filling, replacement of weld lips, addition of step joints, and repair of surface flaws and gouges. The parts were evaluated for mechanical properties, corrosion resistance, weldability, and hydrogen compatibility. This document is a record of the LENS processing of each of these component types and includes process parameters, build strategies, and lessons learned. Through this project, the LENS process was shown to successfully repair or modify metal NWC components.

ACKNOWLEDGMENTS

The authors wish to acknowledge NNSA's NA123 Office of Stockpile Technology for their support of this work. Funding was provided as a Multi-Site Collaborative Technology Investment Project (TI project) titled "Qualification of LENS for the Repair and Modification of NWC Metal Components" with Julianne Levings as Program Manager.

Additional thanks goes to project partner site team leads Chad VanCamp and Jesse Fitzgerald of KCP, Thad Adams of SRNL, and Jason Oberhaus and Tom Mustaleski of Y-12, and Jim McKee of PX.

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FIGURES

1. INTRODUCTION

The Laser Engineered Net Shaping ™ (LENS®) process utilizes a laser, powdered metal, and a computer solid model to fabricate fully dense and fully functional metal components. The LENS Qualification Technology Investment project team, sponsored by NNSA's Office of Stockpile Technology (NA123), set out to achieve process qualification for the LENS process. The development process included the repair and modification of four classes of prototype components provided by the partner sites. These components included reclamation weld bases, sample gas bottles [1], step joint rings [2], and W87 firing set housings [3]. Repairs included building up weld flanges, filling bolt holes, filling oversized bores, and replacing the step joint portion of connecting rings. The materials utilized in the repair of these four parts are 304L and PH13-8Mo stainless steels. For each part, the LENS processing parameters are given to provide a starting point for future LENS repair processes.

1.1. Purpose

The purpose of this document is to record the development and LENS repair/modification of prototypical NWC components. This record will serve as a guide for product and process engineers interested in utilizing LENS to repair and modify components. Along with the record of the repairs performed during this project, the authors give lessons learned to promote success in the use of LENS in high rigor metal components.

1.2. Scope

This document includes a record of the LENS repair of NWC prototype metal components as performed during the "Qualification of LENS for the Repair and Modification of NWC Metal Components" technology investment project [4] sponsored by NA123 Office of Stockpile Technology. Included are the processing parameters and images of fixtures and repaired parts. The document includes the repair of 4 sets of metal components and discusses the method used in this work plus thoughts as to how the process might be improved in future work. The document does not cover testing of the components, as that information is included in another SAND report entitled "LENS Repair and Modification of Metal NW Components: Materials and Applications Guide".

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2. LENS REPAIR OF OVERBORED RECLAMATION WELD BASES

Savannah River National Laboratory supplied sample weld bases with overbored stem holes. In the reclamation process, an old welded stem is removed, the hole is rebored to achieve position and size, and a new stem is welded into place. The provided bases had sample defect holes that had been overbored such that diameters were too large by 0.015", 0.030", and 0.045". The largest diameter overbore was also bored 0.015" too deep. The challenge for the LENS process was to add material such that the hole could be rebored to the correct diameter, a new stem welded in place, and a hydroburst test conducted to test the weld. Several of the welds were then sectioned to inspect the interfaces between LENS, base, weld, and stem materials.

The bore was filled utilizing the 4th axis mounted in the LENS machine with the axis of rotation at an angle of 45 degrees from horizontal as shown in Figure 1. This approach was used to allow the laser to deposit material on both the bottom of the bore as well as the walls. Rings of material with decreasing radius were deposited on the bottom of the bore from the OD to the center. The laser then incremented up one layer and deposited the next layer from the outside to the center again. In this way, the bore was filled. In the initial efforts, the rotational speed of the weld base on the 4th axis was increased as the radius of deposit was decreased such that the apparent feedrate remained constant regardless of radius. The method presented several challenges, however. As seen in Figure 2, as the laser approached the center of the bore, the heat built up and caused excess powder to be entrained in the melt pool, thus creating a bump. By the second pass, the bump became tall enough to grow into the beam even when the laser was depositing at the outer edge. This caused the beam to be obscured at the outer edge and caused the bump to grow at a very high rate all the time. To address this issue, the rotational speed of the axis was increased near the center to considerably higher speeds than used previously. In addition, the very center of the part was not filled on the first several passes. This allowed good material to be deposited on the walls of the part without any obscuration by the center bump. It did mean that the center material was not of good quality (as shown in Figure 3), but this was not important as the hole was going to be bored again anyway. The center material was just provided to allow the hole to be drilled if desired rather than helically interpolated with a mill which is a more time consuming process.

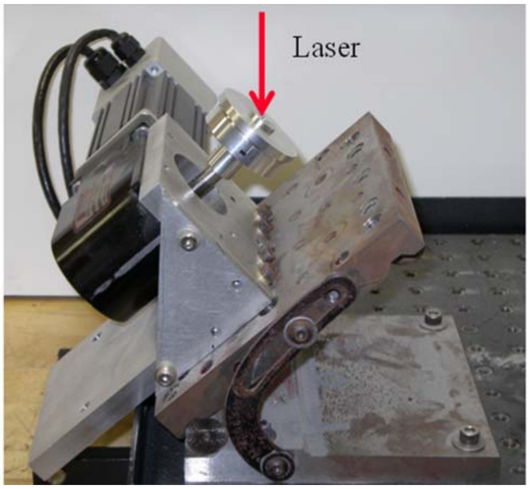

Figure 1. The Reclamation Weld Bases Were Repaired Using the 4th Axis Mounted in the LENS machine at 45° to Horizontal

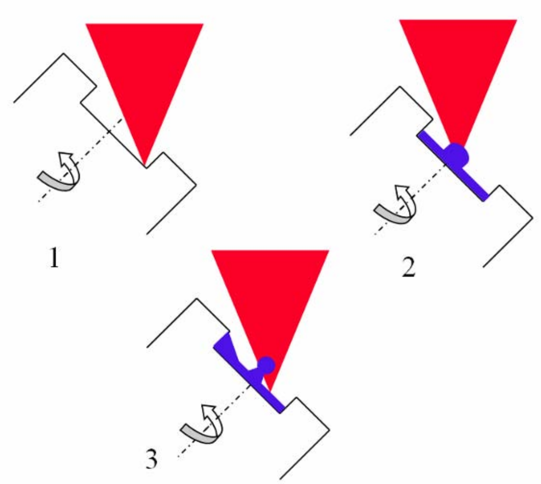

Figure 2. The Repair Proceeded for the OD to the Center of the Bore with the Axis Greatly Increasing in Rotational Speed for Each Subsequent Ring

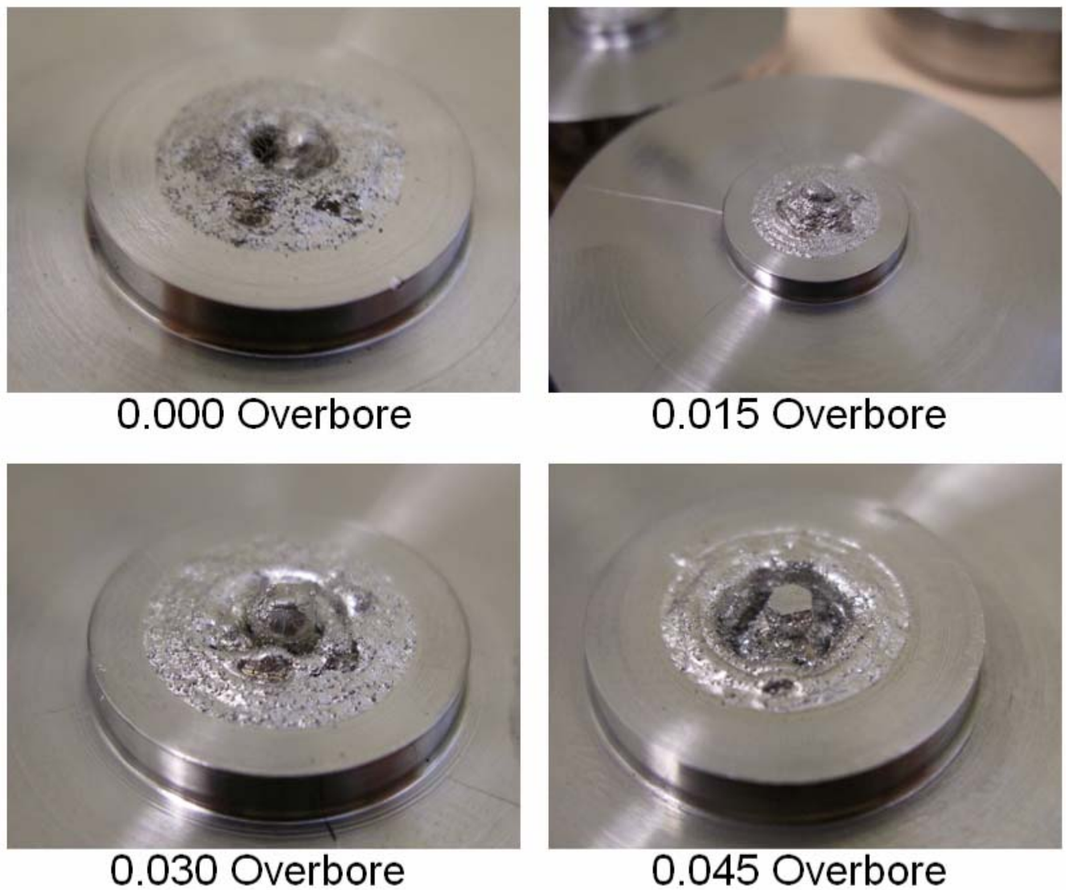

Figure 3. The Repaired Bores Had Excellent Adhesion at the Walls and Bottom of the Bore, But the Material Was Not Very Good At the Center

Figure 3 shows the quality of the deposit from a macro standpoint. It is important to note that differences in the quality of the fill are not due to the diameter of the oversize bore, but are instead due to process improvements made throughout the repair of these components. The 0.045” overbore bases were done first and have the worst center bump. The 0.030” overbore bases had the improvement of higher rotational speed at the center of the deposit, and the 0.000 and 0.015” overbore bases had further improvements in not building all the way to the center of the bore with 0.000” having a slightly improved definition of where the final radius should be for each layer. A difficulty of the process development was that the LENS team had a total of 2 process setup pieces which was insufficient. As shown by Figure 3, considerable improvement in the process was made by the 7^{th} component (the first of the 0.015” overbore repairs). Additionally, as the amount of overbore changed, the diameters of the deposited rings changed which added another variable to the process development challenges. All of the repaired weld bases are shown in Figure 4.

Figure 4. The Full Set of Repaired Weld Bases with Bore Diameters Oversized by (CW from Left) 0.015", 0.030", 0.045", and 0.000"(Nominal)

In addition to filling the weld base bores, the bases had surface flaws to be repaired. These flaws were typical of shipping, usage, and handling scratches as might be found on any part that had been through a number of machining processes. The repaired scratches are shown in Figure 5 with the radial deposit lines showing the location of the scratches. The challenge of repairing these flaws is that the flaws were truly random (created with a hand awl) so process planning was a bit challenging. However, by "blipping" the laser on and off, the end points of straight lines were determined that would cover the flaws.

The process parameters used for the bores are given in Table 1 where they are compared to process parameters determined for large block samples of the same 304L material. The reclamation weld base repairs were all performed without the closed loop melt pool controller since the controller was getting false signals from reflections off the walls of the bore.

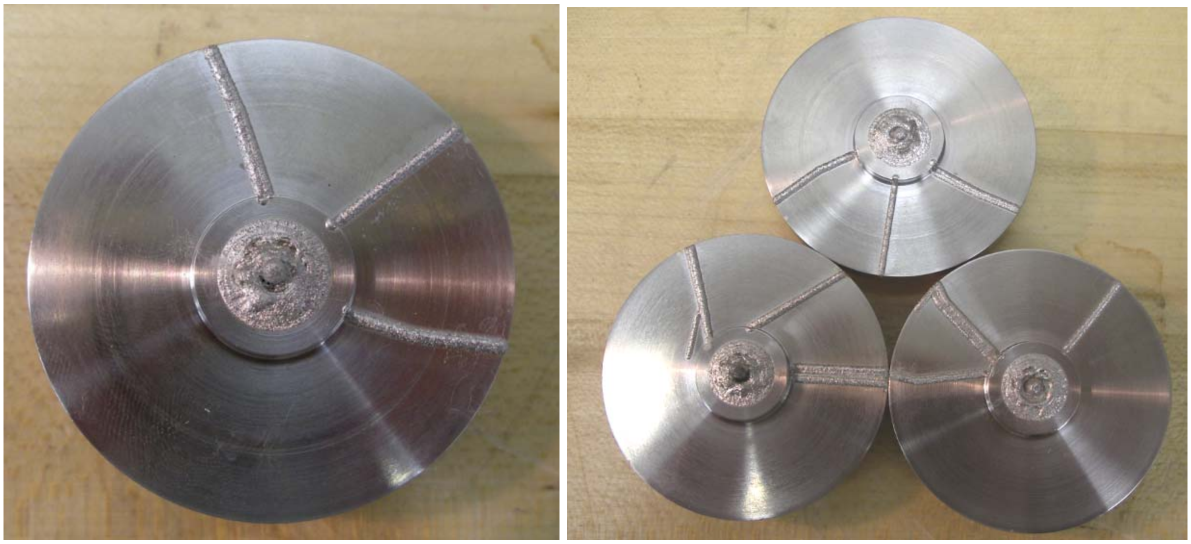

Figure 5. The Radial Lines are Repaired Scratches on the Surface of the Weld Bases

Table 1. The LENS Process Parameters Used for Reclamation Base Repairs As Compared to Process Development Parameters Determined for Large Drill Blocks

	Process Development	Reclamation Base
Powder Flowrate(gpm)	23 (400rpm)	23
Laser Power (W)	355-480W (26-28A) - 575W 1st layer	535 W (29A)
Filter %	80%	70%
WP Intensity	400/150	-
Fill Area (pix)	750/650	-
Border Area (pix)	750/650	-
Axis Feedrate (ipm)	22/20	22+ (faster near center)
Material	304L Drill Blocks	Virgin 304L

Because of the difficulty with the center of each hole, an additional weld base was created. In this weld base, instead of building at a 45°angle, a form tool similar to that shown in Figure 16 was used to slightly angle the side walls of the bore. This bore was then filled from the top with the laser perpendicular to the bottom of the bore and the X and Y axes interpolating a circle. This method quickly filled the bore, provided good adhesion to the bore walls, and gave superior appearance to the previous method. Unfortunately, these parts were not completed in time to be included in the testing so the results of this building technique are unknown.

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3. LENS REPAIR OF SAMPLE BOTTLE SURFACE FLAWS

The second set of components provided for LENS repair was gouged sample gas bottles. These items represented bottles that are rejected by the customer if there is any visible surface flaw in the bottles. Sample gouges were put into each bottle. The gouges were 0.100" wide and either 0.010" or 0.020" deep and were made by an endmill as shown in Figure 6. The bottles were positioned in the LENS machine in a Vee block and toe clamped as shown in Figure 7. The bottle was positioned against a pin at the end of the vee block for positioning and a vee block clamp was used to roll the bottle until the gouge was perpendicular to the laser axis and centered. The toe clamps were then lightly tightened to hold the bottle. The laser, set at low power, traced the edges of the gouge to check alignment. The LENS repair then occurred with the laser depositing 2 or 3 layers (for 0.010" and 0.020" deep gouges, respectively) as shown in Figure 8.

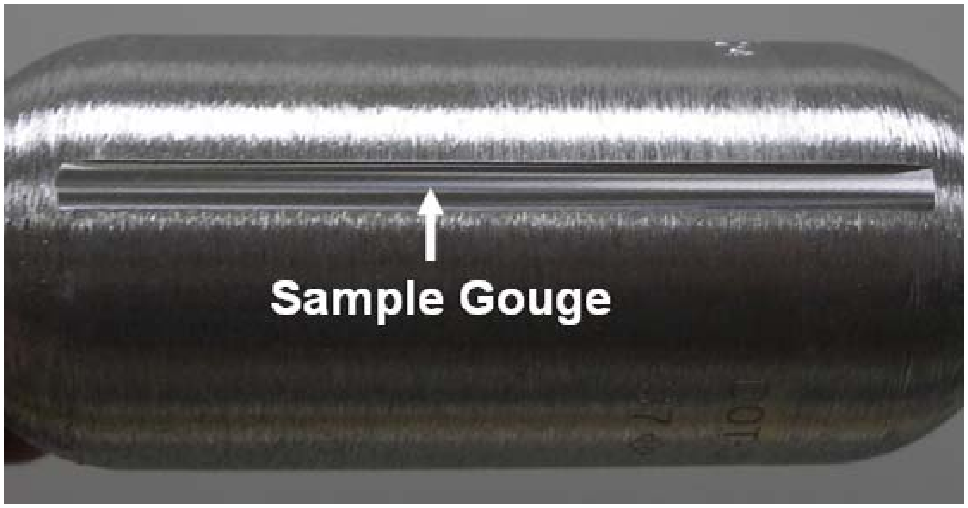

Figure 6. Sample Gouge in Sample Gas Bottle. Gouges were 0.100" Wide and Either 0.010" or 0.020" Deep

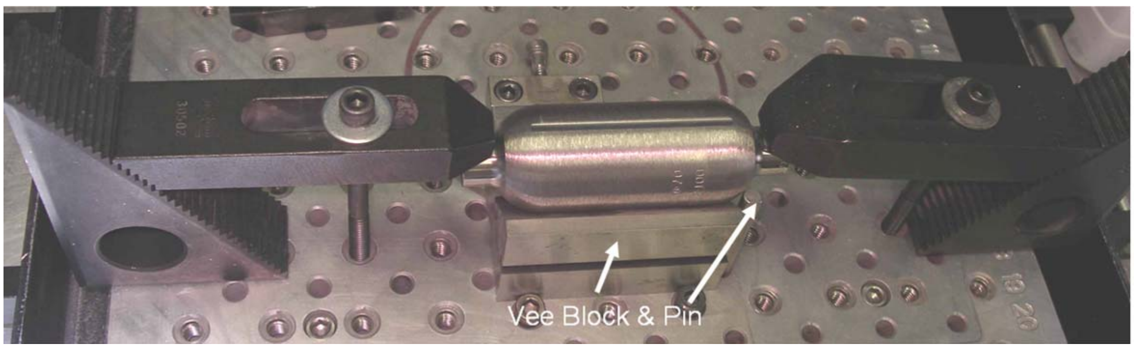

Figure 7. Mounting Fixture in LENS Machine Holding Bottle for Repair

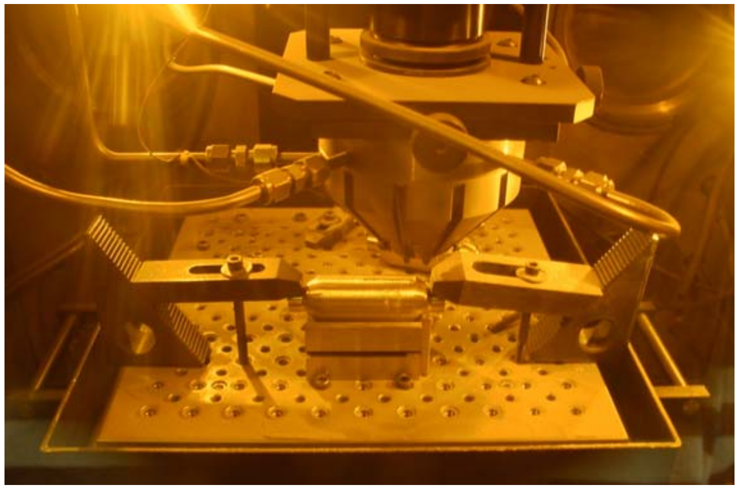

Figure 8 . Sample Gase Bottle Gouge Being Repaired in LENS Machine

The LENS repairs for the sample gas bottles were generally successful with the repaired gouges looking really good as shown in Figure 9. Upon hydrogen charging and burst testing, the bottles all passed the required pressure before bursting, but the bottles did burst along one edge of the gouge. Further analysis and sectioning showed that the LENS material did not quite fill the bottom corner of the gouge in some cases. This bottom corner of the gouge acted as a stress riser causing failure to occur at the site. To achieve better results in the future, it is suggested that a ball end mill or angled mill be used to make the bottom corner easier to fully fill with LENS material and to remove the stress riser. It is expected that this modification would make the failure much less likely to occur at the gouge location. The process parameters for the bottle repair are given in Table 2 along with the process parameters determined for depositing large blocks for comparison.

Figure 9. Repaired Gouge in Sample Gas Bottle

Table 2 . LENS Process Parameters for Sample Gas Bottle Surface Flaws Compared to Parameters for LENS Deposit of Large 304L Blocks

	Process Development	**Surface Flaw**
Powder Flowrate(gpm)	23 (400rpm)	37
Laser Power (W)	350-400W (26-28A) – 575 W 1st layer	-
Filter %	80%	70%
WP Intensity	400/150	300
Fill Area (pix)	750/650	750
Border Area (pix)	750/650	750
Axis Feedrate (ipm)	22/20	22
Material	304L Drill Blocks/	Virgin 304L

4. LENS MODIFICATION OF STEP JOINT RINGS

Step joint rings were provided for repair of the step joint region. These representative geometry rings required that the LENS process replace the step joint portion of the ring so that it could be finish machined and tested for assembly fit. As a representation of the geometry, welded seam stainless pipe was provided for the ring sections and the full set of repaired rings is shown in Figure 10 with the LENS repaired sections shown more clearly in Figure 11. Depositing on pipe provided a challenge because the ring sections were not very round which caused the laser to fall off the edges and deposit a spatter of material down the sides of some of the pipe sections as shown in Figure 12. Minimizing the amount of laser fall off required a lot of work checking and changing program center to try to select the best center point for each ring. This was done by running a program that traced the OD and ID of the ring with the laser at very low power and the operator watching for laser fall off and making adjustments. When the best center was determined, the 1/8" thick by ¼" tall step joint section was deposited on top of the rings. The rings were then machined to final dimension as shown in Figure 13 and assembled for a fit check as shown in Figure 14.

Figure 10. The Full Set of LENS Repaired Step Joint Rings

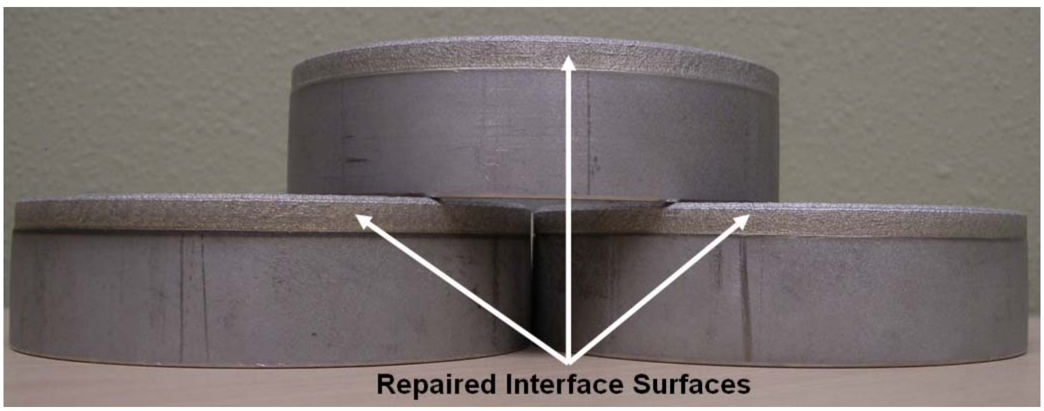

Figure 11. Close Up View Shows the LENS Repaired Section of Step Joint Rings

Figure 12. Some Rings Were Not Very Round Causing The Laser To Fall Down the Side of the Bore Leaving Spatter (Left) with a Round Ring for Comparison (Right)

Figure 13. Two Rings with the Step Joint Machined Into the LENS Material with a Net Shape LENS Ring Shown for Comparison

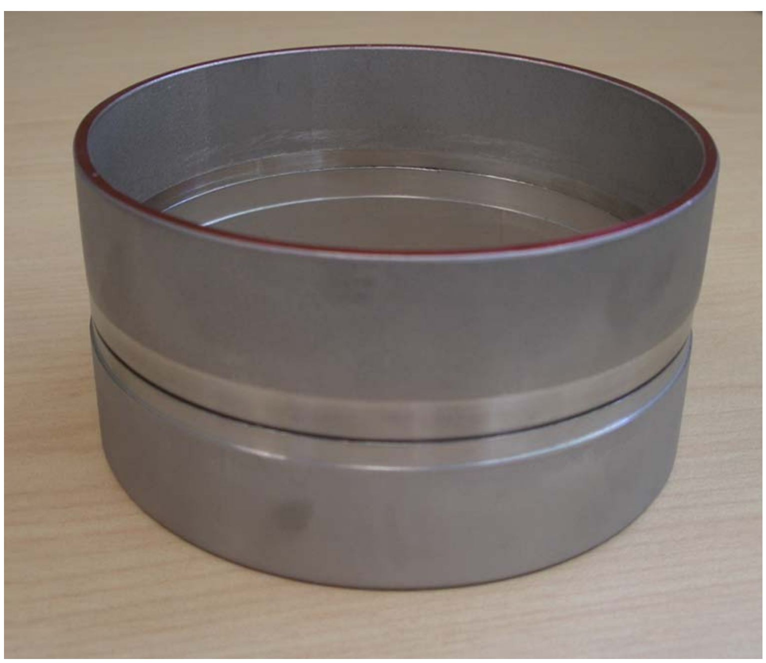

Figure 14. The Assembled Step Joint Rings

The LENS process parameters are given in Table 3 along with a comparison with process development parameters determined on large 304L blocks. The LENS depositing of the step joint rings showed that improved fixturing might be an area of potential improvement. First, the fixturing was done by pinning the ring between 2 bolt heads and a clamping bolt. This method provided too much opportunity to further deform a ring that we already not round. In the future, it would be much better to do these rings with a 3 or 4 jaw chuck that would not only center and positing the ring, but also might help to make it round. The LENS material deposited on top of the ring would then help to hold the ring in a circular geometry. It might also be helpful to mask the lower portions of the ring so that any laser fall off would not cause spatter to adhere to the walls of the rings. A final process improvement would be to randomize the start position of the LENS passes. In this testing, the laser started and stopped at the same X-Y location for each ring deposited. This area then had the seam as well as small irregularities because of the finite time for the laser to develop a melt pool after the shutter opens. The randomization of start location would cause more uniform properties around the ring.

Table 3. LENS Process Parameters for Repair of Step Joint Rings as Compared to the Parameters for Large Blocks

	Process Development	Thin Wall Vessel
Powder Flowrate(gpm)	23 (400rpm)	38 (475rpm)
Laser Power (W)	355-480W (26-28A) – 575W 1st layer	535 W (29A)
Filter %	80%	70%
WP Intensity	400/150	400
Fill Area (pix)	750/650	750
Border Area (pix)	750/650	750
Axis Feedrate (ipm)	22/20	22
Material	304L Drill Blocks	Virgin 304L

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5. LENS REPAIR OF W87 FIRING SET HOUSING WELD FLANGES AND BOLT HOLES

The LENS repair of the W87 Firing Set Housing required deposition on 3 features. These features, shown in Figure 15, were the cover weld flange, the can weld lip, and holes in mounting bosses around the can lip. The cover weld flange and can lip needed to be rebuilt from a machined state and the mounting bosses required that the holes be filled so that they could be drilled and tapped again. The W87 housing is 17-4 stainless and the LENS repair was done with 13-8 stainless, a similar, precipitation hardening material.

The first repair to the W87 housing was the filling of holes. The holes are in bosses that are attached to thin walls on the side of the can. Before LENS repair, the holes were machined using a form tool, shown in Figure 16, which left a steeply angled sidewall to the holes. The form tool was designed to have the maximum possible diameter at the top edge (determined by the size of the boss) and the flattest angle possible to present a face for the LENS process to build upon. Because holes with sidewall angles this steep had not been LENS repaired before, a block was drilled with many holes and the form tool was then used on these holes. Process parameter testing indicated the parameters that would be most successful for filling the hole, so an attempt was made to fill one of the holes in the W87 housing using these parameters. The result was a very hot build that discolored all of the area around the boss. The process parameter block and discolored boss are shown in the top row of Figure 17. Though the geometry of the hole was exactly the same as had been used in the process parameter development, the surrounding geometry was not the same which caused the heat conduction pathways to be different as well. To make the process development and actual part builds match, one of the two items had to be modified to provide similar heat conduction to the other. It was determined that creating process development bosses on thin walls would be prohibitively expensive and time consuming, so the real part was made to mimic the process development block with the addition of a heat sink. The aluminum heat sink allowed the heat to conduct away from the boss so that the LENS deposit did not discolor the surrounding geometry. The heat sink and resulting hole filling are shown in the bottom row of Figure 17. In addition to the heat sink block, it was necessary to add a plate underneath the hole for the LENS material to use in creating a melt pool. The plate was clamped in place for the build and was relatively easy to remove either by drilling the hole at which point the plate usually separated by itself or by milling the plate off the hole. This exercise was a valuable lesson in the filling of holes and showed the ability to LENS deposit in the holes. Additional process development would be necessary to make this repair completely successful as the bottom of the holes had incomplete adhesion. A more extensive process development might determine that the process would benefit from total rebuilding of the bosses rather than just hole filling. However, hole filling was of more interest to first users than boss replacement.

The W87 repair also required that the cover weld flange, a curved feature, be repaired by building up the weld lip to allow machining and rewelding. Some sections of the lip are straight and some have compound curves. A fixture for the part was designed and manufactured by KCP to allow accurate location of the part in the LENS machine as shown in Figure 19. Because of the 2½ dimensional nature of the LENS machine at the time of this repair, it was necessary to repair this part with the part sitting as shown. The laser was traversed in a conformal path along the weld flange sides, up and over the arcs, and around the compound curve near the fixture. With the newly installed elevation and azimuth rotary axes in the LENS machine, this part would be repaired differently with the part rotating under the laser to keep the incident beam normal to the flange face. The face required multiple layers with 0.020" nominal layer thickness. The face was a challenge to fill because it tended to be thick at the outer edges and sometimes knife-edge thin at the inside edges, thus giving different heat conduction paths. In one location the face was completely missing as is shown in Figure 18. The LENS team attempted build up the face in this location, but was somewhat unsuccessful due to the angle of the incoming laser, a difficulty that would no longer be an issue. Overall, however, the flange was satisfactorily repaired. There was some possible lack of adhesion discovered in the weld flange during the machining stage. In these areas, it is surmised that the LENS deposits for the large arc did not sufficiently overlap the straight passes on the edges of the flange. A process improvement would be to offset the passes on alternating layers to assure full adhesion layer to layer and to eliminate any possibility of voids between hatch lines.

The final repaired feature was the can lip which was repaired by placing two side-by-side LENS passes around the periphery of the can as shown in Figure 15. Again, KCP created a fixture for precise location of the housing as shown in Figure 20. Because of the axis limitations of the LENS machine at the time of the repair, a tall feature at one end of the lip (left side of Figure 21) prevented the entire can lip from being repaired. The feature would not prevent the repair on the current LENS axis system with tilt capability. This repair was easy to align and quick to repair. During testing, it was discovered that there was incomplete bonding between the parallel LENS passes. This incomplete bonding could be easily avoided by programming an overlapping LENS pass in between the two parallel passes.

The process parameters used for the W87 firing set housing repairs are shown in Table 4. As with the other repaired parts, the housing would have benefited from additional process development time. This is especially true of the housing where the team had only 3 housings and each was going to be tested, so each needed to be repaired as well as possible.

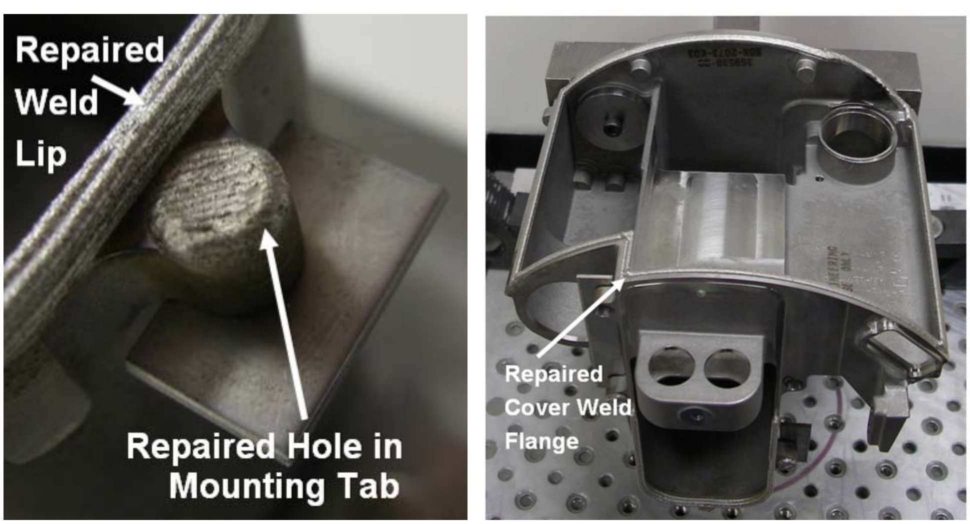

Figure 15. W87 Firing Set Housings Were Repaired by the LENS Process. Repaired Features Includ the Can Weld Lip and Mounting Holes (left) and the Cover Weld Flange (right)

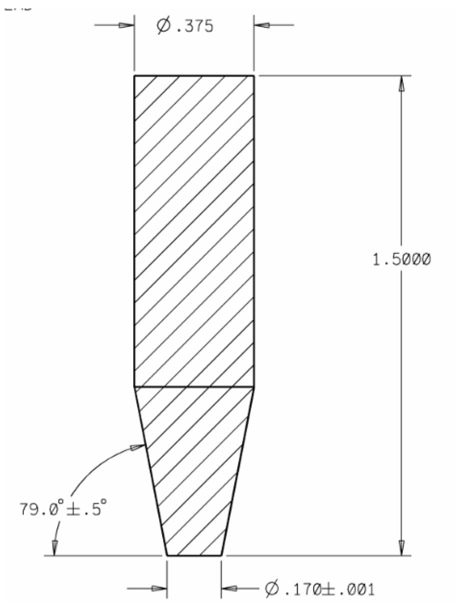

Figure 16. This Form Tool Was Used to Bored the Bolt Holes Before LENS Depositing. Even this Steep Angle Gave Sufficient Surface for Adequate LENS Adhesion

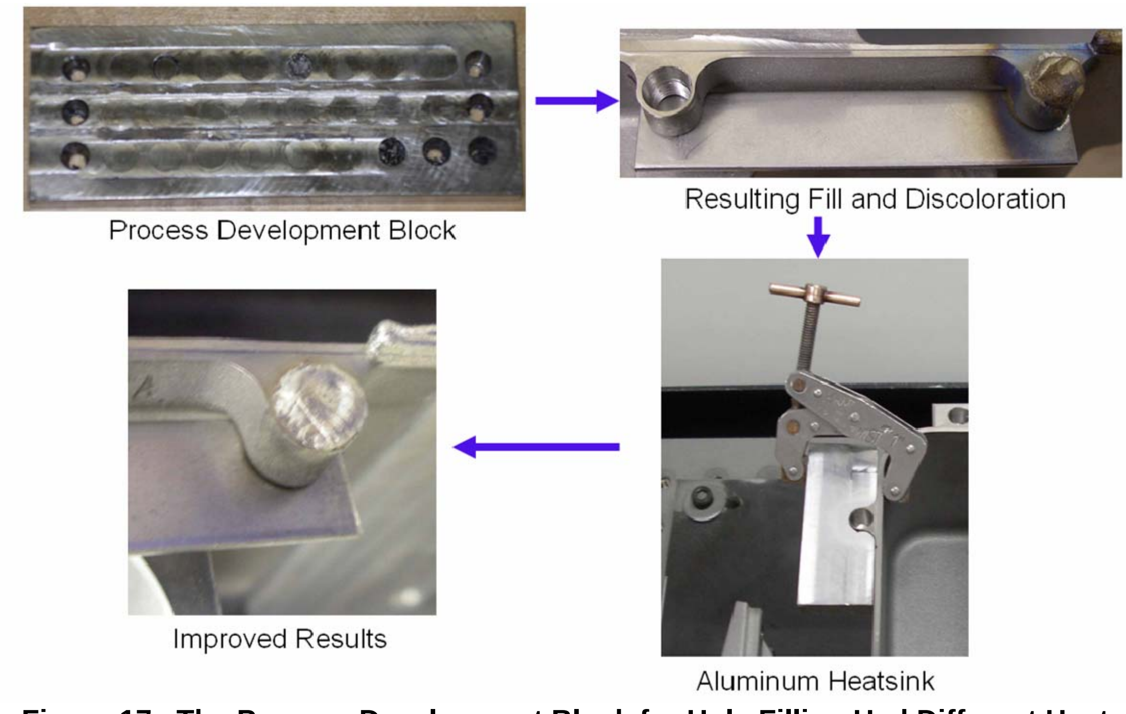

Figure 17. The Process Development Block for Hole Filling Had Different Heat Conduction Characteristics Than the Real Part Resulting in Discolored Parent Material. An Aluminum Heat Sink was Added and the Hole Filling Improved Significantly.

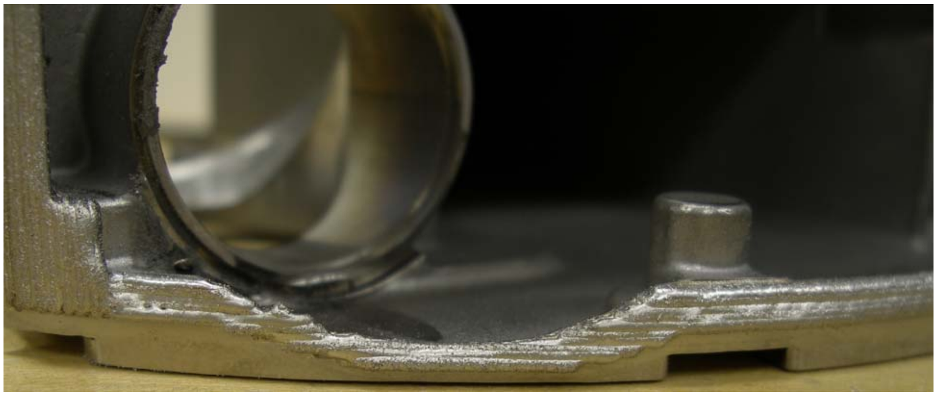

Figure 18. This Cover Flange Weld Lip Feature Presented Problems Due to No Existing Material On Which To Build the LENS Weld Flange. This Would Be Easier with 5 Axis Depositing or a Different Fixture.

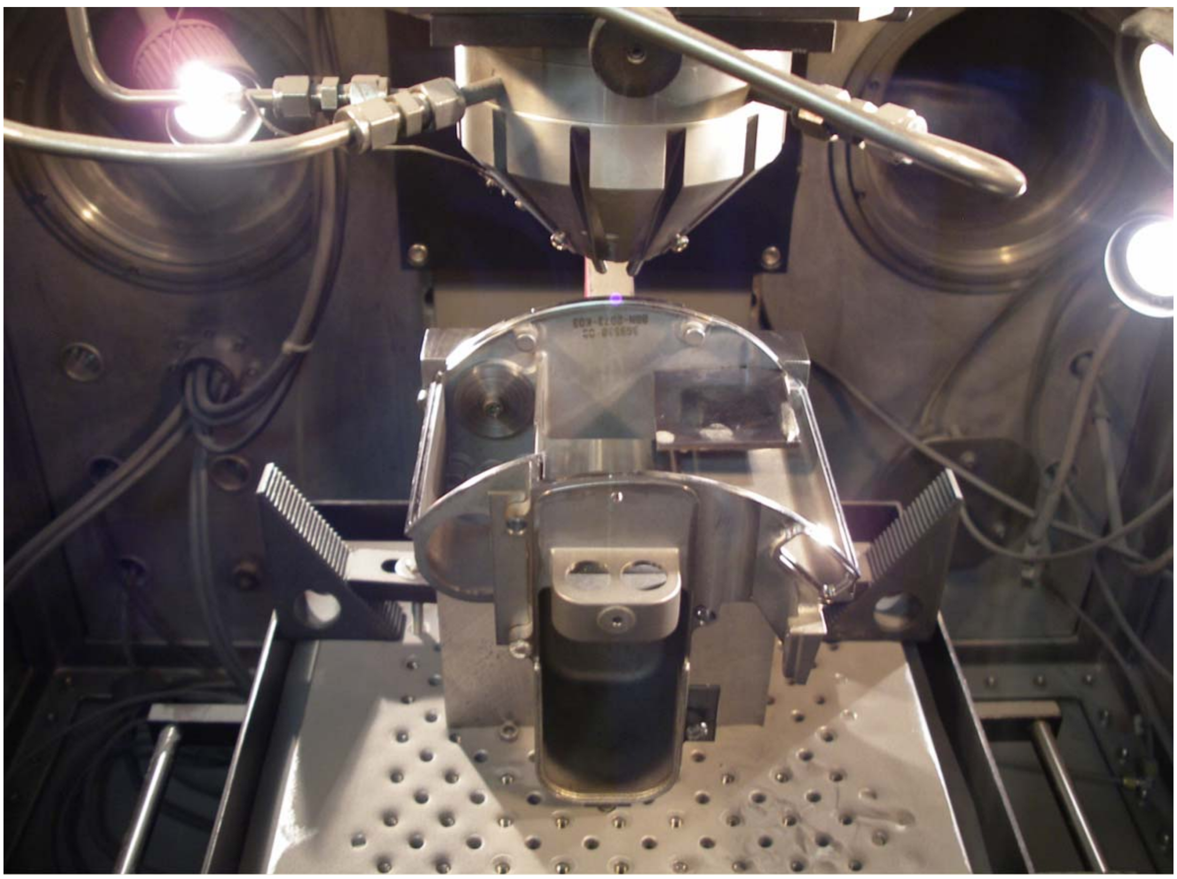

Figure 19. The W87 Firing Set Housing in the LENS Machine for Repair of the Cover Weld Flange.

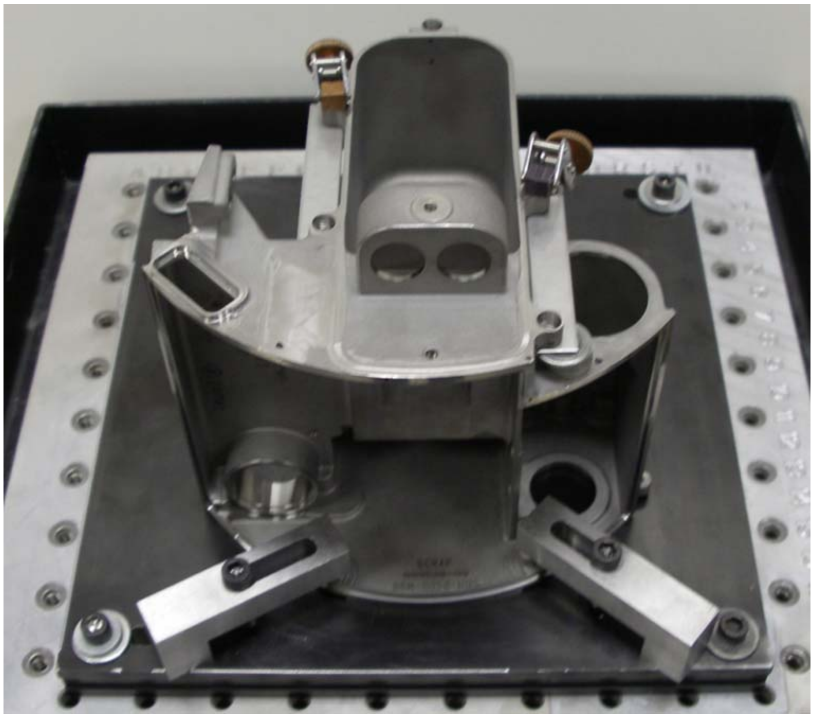

Figure 20. The Fixture for Repair of the Can Weld Lip and the Bolt Holes on the W87 Firing Set Housing.

Figure 21. The Completed Can Lip and Filled Bolt Holes. Note the Large Feature on the Far Left Prevented the Entire Can Lip form Being Completed. Also Note the Support Plate Used Under Each Hole to Help the LENS Build Start

Table 4 . The LENS Process Parameters for the the W87 Firing Set Housing Compared with Parameters Determined for Large Blocks of PH13-8Mo

	Process Development	**W87 Housings/Holes**
Powder Flowrate(gpm)	23 (400rpm)	24/21
Laser Power (W)	290W (25A)	245 W (24A) /190W (23A)
Filter %	140%	140%
WP Intensity	580	-
Fill Area (pix)	600	-
Border Area (pix)	600	-
Axis Feedrate (ipm)	22	18
Material	13-8 Drill Blocks	Virgin 13-8

6. CONCLUSIONS

The LENS Qualification Technology Investment Team set out to show the applicability of LENS-repaired components to high rigor applications such as weapons. Each partner site provided prototypical components with sample defects or repair scenarios that required the development of new repair processes. The component repairs utilized 304L and Ph13-8Mo stainless steels. The component repairs showed the capability of LENS to successfully repair weld flanges, misplaced or stripped holes, oversized bores, scratched and gouged surfaces, and to add step joint material to rings. The components repaired have broad applicability across the NWC and show LENS to be a viable means of saving valuable parts that have been damaged, incorrectly machined, and cast in an undersize condition. The successful repair of these parts has shown the potential opportunity to save significant cost in product development cycles as well when features could be moved or added to existing development hardware rather than waiting for new hardware to be manufactured.

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