LENS Repair and Modification of Metal NW Components:
Materials and Applications Guide

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Qualification of LENS® for the Repair and Modification of NWC Metal Components

A Multi-Site Technology Investment Project

EXECUTIVE SUMMARY

Laser Engineered Net Shaping ™ (LENS®) is a unique, layer additive, metal manufacturing technique that offers the ability to create fully dense metal features and components directly from a computer solid model. LENS offers opportunities to repair and modify components by adding features to existing geometry, refilling holes, repairing weld lips, and many other potential applications. The material deposited has good mechanical properties with strengths typically slightly higher that wrought material due to grain refinement from a quickly cooling weld pool. The result is a material with properties similar to cold worked material, but without the loss in ductility traditionally seen with such treatments. Furthermore, 304L LENS material exhibits good corrosion resistance and hydrogen compatibility.

This report gives a background of the LENS process including materials analysis addressing the requirements of a number of different applications. Suggestions are given to aid both the product engineer and the process engineer in the successful utilization of LENS for their applications. The results of testing on interface strength, machinability, weldability, corrosion resistance, geometric effects, heat treatment, and repair strategy testing are all included. Finally, the qualification of the LENS process is briefly discussed to give the user confidence in selecting LENS as the process of choice for high rigor applications.

The testing showed LENS components to have capability in repair/modification applications requiring complex castings (W80-3 D-Bottle bracket), thin wall parts requiring metal to be rebuilt onto the part (W87 Firing Set Housing and Y-12 Test Rings), the filling of counterbores for use in reservoir reclamation welding (SRNL hydrogen compatibility study) and the repair of surface defects on pressure vessels (SRNL gas bottle repair). The material is machinable, as testing has shown that LENS deposited material machines similar to that of welded metal. Tool wear is slightly higher in LENS material than in wrought material, but not so much that one would be concerned with increased tooling cost.

The LENS process achieved process qualification for the AY1E0125 D-Bottle Bracket from the W80-3 LEP program, and in the effort, also underwent testing in weapons environments. These tests included structural dynamic response testing and drop testing. The LENS deposited parts were compared in these tests with conventionally machined parts and showed equivalency to such an extent that the parts were accepted for use in parallel path subsystem-level weapon environment testing. The evaluation of LENS has shown that the process can be a viable option when either complete metal parts are needed or existing metal parts require modification or repair. The LENS Qualification Technology Investment team successfully investigated new applications for the LENS process and showed that it has great applicability across the Nuclear Weapons Complex as well as in other high rigor applications.

ACKNOWLEDGEMENTS

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1 PURPOSE AND SCOPE

1.1 Purpose

This document is intended to be a guideline for those interested in using Laser Engineered Net Shaping ™ (LENS®) for the modification, repair, and fabrication of metal components. The document provides a basic understanding of LENS, guidelines for designing parts for LENS, and guidelines for the manufacturing of parts using LENS. The document also contains reports of case studies which should assist engineers with design, product, and process responsibilities to determine that applicability of LENS technology to a specific application.

1.2 Scope

This document gives a basic understanding of the LENS process, its capabilities, and its limitations. Included are the results of materials, machining, corrosion, and hydrogen compatibility studies. Also included are case studies of example components and repairs completed by the LENS process. The document is currently limited to 3 materials: PH 13-8 Mo, 304L, and 316L stainless steels. However, the results of those tests are indicative of possibilities with other materials and should help a designer to decide if LENS is a potential manufacturing solution. It is hoped that this document will be a living document that will continue to expand and to include other materials and other example applications.

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2 INTRODUCTION TO LENS MODIFICATION, REPAIR, AND MANUFACTURING TECHNOLOGY

Laser Engineered Net Shaping™ (LENS®) is a laser deposition process developed at Sandia National Laboratories. The process is capable of depositing many types of metal onto substrates using an Nd:YAG laser. With the proper process parameters, LENS depositions can be composed of fully dense material with properties similar or superior to those of wrought materials. The ability of LENS to deposit freeform structures on metal substrates makes this process an ideal candidate for the production and repair of castings and machined structures. This document outlines the types of modifications and repairs that are possible using LENS as well as the manufacture and fabrication of LENS parts.

2.1 Process Description

The LENS process utilizes a laser and powdered metal to form metal parts from computer solid models. The basic system consists of a laser, a powder feeder, a set of motion controlled axes, a substrate material, an inert atmosphere, and a closed loop melt pool control system. A schematic of the process is shown in Figure 2.1.A. The laser is focused on a metal substrate creating a small molten pool. The powder feeder feeds powdered metal into a flowing argon stream which is directed into the melt pool by 4 nozzle tips. The powdered metal melts and then the melt pool solidifies into a bump as the axis moves the melt pool to a new location. When moved smoothly along a trajectory, a raised line is created. The computer model, which has been divided into layers and each layer divided into lines, then directs the creation of the part: line by line and layer by layer a metal component is formed.
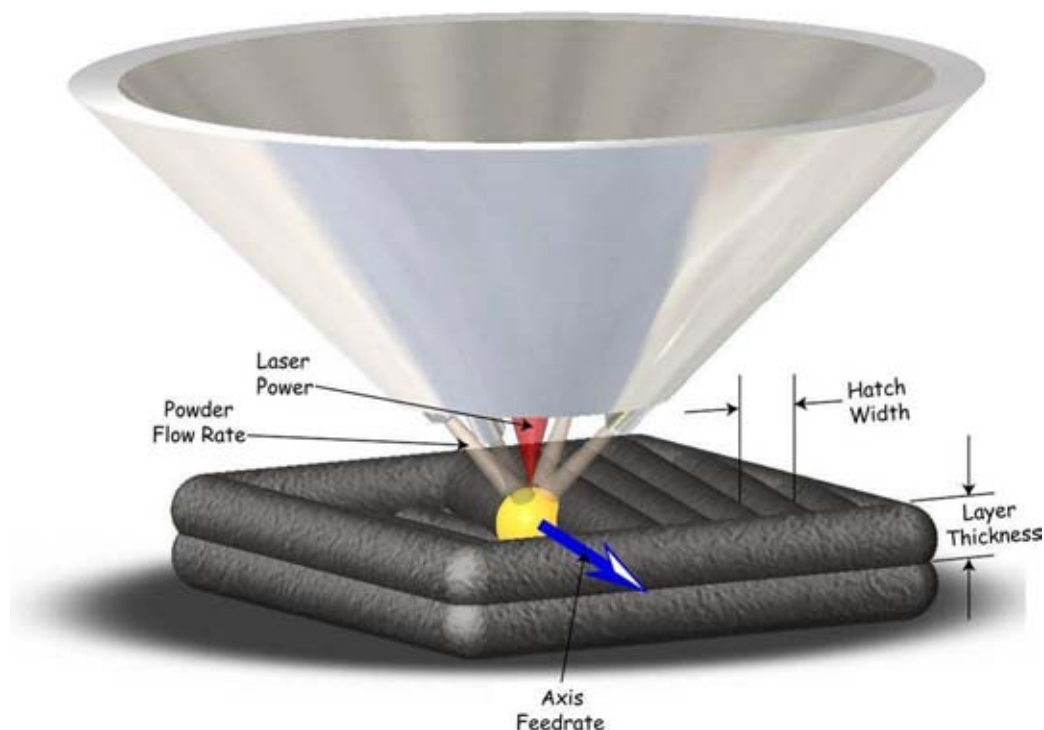
Figure 2.1.A: The LENS Process Showing Important Process Parameters

The Figure also shows several of the most important process parameters which can be varied to change the properties of the part. *Laser power* has to be sufficient to melt the powder but not so high as to ablate the material. In many instances, this is controlled by a closed-loop melt pool controller which applies a PID loop to maintain a constant area of the melt pool above some chosen intensity value. The *powder flow rate* can be changed as well. More powder builds taller parts, but can cool the melt pool to such a point that the metal powder is not melted causing inclusions in the finished part. The *layer thickness* determines how much of the previous layer is remelted in the current layer. Too large a layer thickness will also cause the laser focus to advance too quickly for the material ending in a part that does not meet geometric requirements. The *hatch width* determines the amount of mixing between lines deposited within the same layer. Finally the *axis feedrate* determines how fast the melt pool cools in addition to affecting the height of the build by increasing or reducing the amount of time that the melt pool is available to receive powder at a certain position.

Sandia National Laboratories' LENS machine is shown in Figure 2.1.B. The system is composed of 5 major subsystems. The laser subsystem is of sufficient size to melt metal and the wavelength will determine the laser's compatibility with specific materials. SNL's system utilizes a 1200W, continuous wave, Nd-YAG laser. However, other LENS systems contain solid state lasers and laser power ranges from 500-18,000W. The laser system may require additional optics to remove white light and to expand, collimate, and focus the laser beam. Also essential is a shutter and beam dump which can control when the laser power does and does not reach the substrate and, subsequently, when the process does and does not deposit material. While the laser is a reliable, consistent power source, flash lamp performance does vary over time and is an impediment to process repeatability if not paired with a closed loop melt pool controller.

The closed loop melt pool control system works closely with the laser to create consistent, repeatable process conditions. The melt pool controller views the light emitted from the melt pool using a CCD camera looking through the same focusing lens as is used by the laser. The controller processes the melt pool image and determines a boundary that surrounds the portion(s) of the melt pool that are above a certain intensity. The controller then strives to make the area enclosed in the boundary match a process target by increasing and decreasing the laser power. It is often necessary to have different target areas for border, fill (or hatch), and overhanging conditions. Additionally, different materials have significantly different emissivities that will exhibit very different intensities on the melt pool controller. It is necessary to have different neutral density filters in front of the controller camera to prevent saturation of the detector and the differing emissivity values may require a unique filter combination for each new material. So, in developing process parameters for a new material, the process engineer must determine the correct neutral density filter, threshold intensity, hatch area, border area, and overhang area.

The third major subsystem is motion control. A set of axes must be driven to create the geometry. A minimum of 3 axes are needed, though there can be many more axes to achieve greater capability. The axis controller must also drive digital outputs to control items like the shutter state and to communicate build status to the closed loop melt pool controller.

The fourth major subsystem is the powder delivery system. This system typically consists of a stream of pressurized process gas, one or more powder feeders to meter powder into the gas stream, and a powder distribution system. Pressurized gas can be supplied as virgin gas from a tank or dewar, or as recycled process gas that is re-pressurized by a compressor. Powder feeders can be of many types, with screw and pea-planter types being the most popular. And powder distribution systems can consist of 4-8 nozzles or concentric flow nozzles. Most systems also include a plenum/distribution manifold before the nozzles which removes pulsation and equalizes the flow between the different nozzle tips.

Figure 2.1.B: The LENS Machine at Sandia National Laboratories

The fifth and final LENS subsystem is the purified environment (typically argon with <5ppm oxygen) to cause the material produced to be as similar as possible to the composition of the metal powder used in the process. The argon is often re-circulated in the system through compressors and scrubbers that work to remove oxygen, but may also be supplied from gas cylinders or dewars to eliminate the very expensive and somewhat temperamental scrubbing and compression systems.

2.2 General Process Capabilities

The LENS process is capable of creating free-form 3-D objects from powdered metal by directly utilizing a computer solid model. The user first creates a solid model of the desired part. The part is then exported as a .stl (stereolithography) file. The .stl file is read by an

automatic code generator such as Sandia National Laboratories' "Damocles" which prompts the user for processing parameters, and then creates the M&G code by which the motion control axes are driven. Additionally, the M&G code contains commands that open and close the shutter and communicate program data to the closed-loop area controller. From this file, the part is built.

Geometry Capabilities – The LENS process offers the capability to create parts that would be difficult or impossible to create by any other means. Thin wall features of great height are possible and they can contain closed volumes or volumes that are not accessible by typical machining processes. Several LENS produced parts are shown in Figures 2.2.A and 2.2.B. The Figures show many of the possible geometric and material options available from the LENS process.

Figure 2.2.A: Examples of Parts Produced by LENS Including Nitinol Lugs (A), 304L Tubes (B), Tool Steel Mold Insert (C), Hollow Turbine Blade (D), 316L Housing (E), and Freeform Optimized Structure Section (F). Also Shown Are Materials Test Samples (G, H, I) and Tensile Samples (J) Machined From LENS Deposited Columns (K)
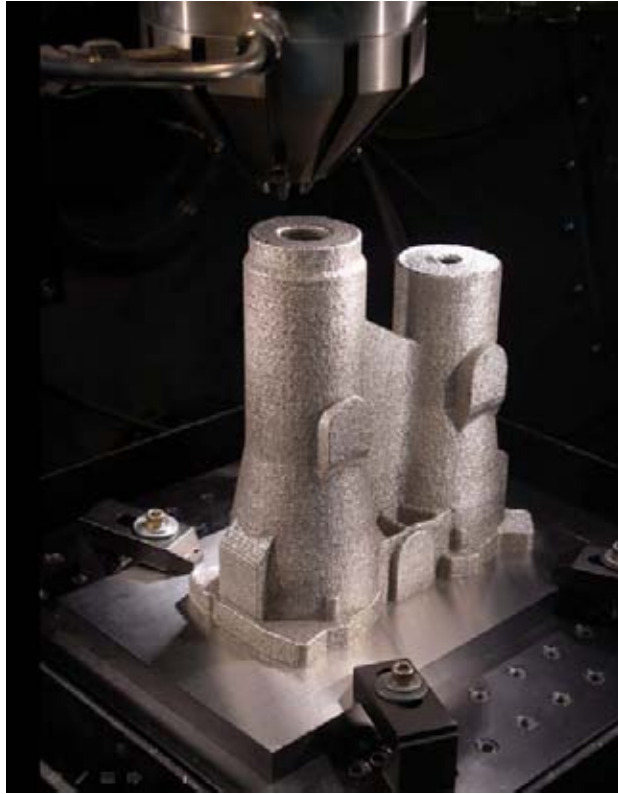
Figure 2.2.B: Titanium-6%Al-4%V Aerospace Component Produced By LENS

Figure 2.2.A (A) shows LENS-produced hex nuts on NiTi (nitinol) shape memory alloy shafts, a material that is notoriously difficult to weld. Figure 2.2.A (B) shows thick wall cylinders of stainless steel. Figure 2.2.A (C) shows a tool steel mold, the electrodischarge machining (EDM) electrode used to machine ½ of the mold, and a molded part produced by a similar mold that was fully machined. This mold is unique because it has integral conformal cooling passages that loop up through the mold face, a feature available only through LENS. Figure 2.2.A (D) shows a hollow turbine blade that provides cooling passages internally. Because of the twist in the blade, LENS is uniquely capable of building this part as one piece. Figure 2.2.A (E) shows an electrical housing in which all of the wall and boss structures were deposited by LENS and then finish machined. And Figure 2.2.A (F) shows a portion of a torsional shaft optimized for low weight and high strength. Figures 2.2.A (G-K) show samples produced for machinability studies, corrosion studies, hydrogen compatibility studies, and mechanical property studies. And, finally, Figure 2.2.B shows a Ti-6-4 Aerospace Component which was produced using the LENS process. This component is an excellent example of an application for which LENS was highly advantageous. This part took nearly 60 hours to deposit using the LENS process but was completed in 1 week including the LENS deposit and post process heat treatment. This is compared to the conventionally machined component which required 3 weeks of machining to reach the rough machined point of the LENS part. Because of the difficult machining properties of titanium, it is highly advantageous to use LENS to achieve a near-net shape part and then to proceed from that point with conventional machining.

It is important to note that LENS is a near-net shape process. The parts produced by LENS may require finish machining on some features in a manner similar to that which is done on castings. Most LENS machines are 2½ dimensional machines meaning that they lay down a layer using the X and Y axes, increment up in Z, and then put down another layer. This process builds parts with excellent microstructure, but limits overhang capability to 45°. This limitation is because LENS creates a melt pool in existing material and then blows powder into the melt pool to build up the part. If the process is building a 45° overhang, only ½ of the weld pool is supported and the other ½ must hang on by surface tension. The swirling gas at this interface further reduces the ability of the weld pool to stay connected with the part. If overhang of more than 45° is needed, there are several options. First, there are a number of 5 axis LENS machines which would be able to create the part. Second, a part can be built with support structures created under the overhanging material. This often significantly extends the time needed to create a part. Third, the part can be re-fixtured and the process can build in a different direction with respect to the part while not violating the 45° rule. This can sometimes be accomplished in 2½ dimensional machines by introducing a rotary axis or indexing table. Finally, LENS offers a very unique capability in creating conformal internal passageways that cannot be produced by any other method except for casting. These passageways can provide conformal cooling to mold cavities or provide internal cable routing that is integral to the part.

Potential Materials - The LENS process has the capability of building parts out of most metal materials. Much work has been done on tool steels, stainless steels (especially 304L, 316L, PH 13-8 Mo), Inconels, Ti-6%Al-4%V, high strength/toughness steel alloys like AerMet 100, and others. Generally, the following guidelines are given for materials. It is difficult to utilize aluminum or copper alloys in machines that utilize lasers for the power source due to the high reflectivity of the metals to laser wavelengths. If aluminum and copper are needed, a machine equipped with an electron beam must be utilized, and these machines are rare outside of research settings. The other limitation is for materials with very high melting temperatures. This limitation can generally be overcome by utilizing lasers with higher output power and sometimes reduced spot size. Tungsten can be done on some machines, and materials with even higher melting temperatures typically present problems. Finally, LENS offers the unique capability to grade the material composition. So-called "Functionally Graded Materials" are produced by changing the composition of the powder being introduced into the melt pool in real time as the build progresses. This can be done by premixing the powder or can be achieved by utilizing multiple powder feeders that feed into the same supply hose. By independently varying the mass flowrate of the powder from each powder feeder, the material can be alloyed "on-the-fly" to create parts with different performance characteristics at different locations within the build.

2.3 Design Consideration for LENS Components

LENS offers many opportunities for part fabrication in relevant engineering metals. In addition, LENS offers the opportunity to make repairs or modifications to existing parts with a highly controlled process that provides enhanced microstructure and strength, often with no penalty in ductility. LENS has been demonstrated for the repair of weld lips and flanges, surface flaws, holes, and misplaced features. Demonstrations have also shown the ability to add new features including thin wall structures and bosses. The process can be used to add

material to undersize castings and to allow reversal of machining mistakes. In many cases, it may be more economically advantageous to build up a near-net shape part than to machine one from a solid billet. These capabilities make LENS a unique tool for the designer.

In order to best utilize the LENS process, the designer and/or process engineer may consider some advantageous part modifications. The LENS process induces heat in the material from the melt pool, so post-process heat treat annealing is often necessary to relieve any thermally induced stress. Fortunately, the LENS material reacts to heat treatments similarly to wrought material, so determination of the heat treat cycle can follow industry standard practices. The designer should consider which areas require a machined surface finish and which areas can maintain the LENS surface, much like utilization of a casting. The designer is free to do very tall, thin wall structures that aren't possible by other means. The designer may also include internal cavities that are inaccessible from the outside of the part. When weight and stiffness are of importance, LENS offers the opportunity to create monolithic structures where one might have used bolted or riveted joints in the past. LENS also allows the user to have sharp (square) internal features and corners since there is no reliance on tool radius in the as-deposited state. Some decisions will have to be made, especially regarding overhanging features, through holes, cantilevered sections, etc. If using a 5-axis LENS machine, there is no concern, but if using the more standard 2½ dimension machine, it may be necessary to provide support structures or to allow holes to be introduced after the process by conventional machining processes.

Over the course of several years, the LENS team has developed some guidelines for designers.
A. The LENS manufacturer will need a model that is slightly oversize to account for the near-net shape of LENS parts, providing sufficient material to be removed in finish machining. Recommended allowances are 0.020-0.030 to each wall surface.
B. It is recommended that holes that will be drilled be removed (i.e. filled in) from the model that is built by LENS. The LENS process can leave these holes in the build, but it is extremely difficult to guide the drill to any location other than the average center of the LENS build. It is typically more accurate, faster to build, and as efficient to drill when the hole is being drilled in solid LENS material.
C. The designer is free to utilize materials other than the base material for repairs and modifications. This is often done to hard coat a part's face to increase wear resistance. The designer must consider any mismatch in coefficient of thermal expansion before specifying this type of repair to prevent undue stress from being introduced into the part.
D. It is important for the designer to alert the process engineer to any areas of surrounding existing geometry that may have tight tolerances or be especially susceptible to heat input. This will help the process engineer to determine places that may require heat sinking. The warning is especially important if the item to be repaired is an assembly and already has electronics or other parts installed.

2.4 Manufacturing Considerations for LENS Components

The LENS process offers the manufacturing community a unique opportunity for creation of features where material did not previously exist. However, utilization of LENS requires the process engineer to think differently than for conventional machining. Instead of envisioning

how to remove material from a solid block or casting, there are often opportunities where the engineer might start with a portion of the component and then add material to create the desired geometry. The original substrate material could become part of the final object or could be cut free after depositing or machining is completed. To help the process engineer, the following list has been compiled with some of the most important aspects that should be considered when planning to utilize LENS.

A. Part Preparation – The utilization of LENS for repairs and modifications will often require that the existing geometry be modified to accept the LENS geometry. In choosing what features and how much to remove, the following items are important. Remove features to a point such that the LENS deposit will be supported and not overhanging. Consider access issues; if too much material is removed next to tall existing features, it may not be possible to get the LENS nozzle in to make the feature. It may require removal of existing surrounding geometry to gain access. And finally, when removing material, the remaining surfaces should be as close as possible to being normal to the incoming laser beam. When cutting a pocket that will be filled with LENS, it is advantageous to slope the walls rather than using straight vertical walls. Similarly, it is difficult to fill inside corners and bottom corners in a pocket, so radiusing these features will help lead to greater success. And, when filling a hole or a bore, it is helpful to taper the walls as well. This can be done with a form tool or other process. Even a fairly steep taper will give improved interface adhesion.

B. Surface Preparation – The LENS process will entrain whatever surface contamination exists into the final material assuming that the contamination isn't consumed by the laser or doesn't burn away. To help maintain material purity, it is suggested that the surface of the part be cleaned by standard cleaning procedures such as those used before welding. If this is not possible for some reason, such as existing electronics elsewhere in the part, then the laser beam may be traversed over the surface at a lower power than is used for part depositing. The beam will ablate away many of the contaminants.

C. Fixturing Concepts – When using LENS for the repair of components, it is always challenging to determine the optimum fixturing procedure for the job. Fixtures need to be significantly robust as to not deflect under axis acceleration or under the weight of the part filled with powdered metal. The fixture should have features that can be used to align the part with the machine. It is usually advantageous for the part to be in intimate contact with the component over a large enough surface area so as to help with heat conduction from the part. The fixture should be tolerant of powdered metal in any clamping mechanisms and should be designed to shed powder in any critical areas. Finally, the fixture should address stress and deformation induced by heat. There are 2 primary ways to address this. The first is to fixture the part with significant force so that it cannot deflect during material deposit. This method locks a lot of stress into the part that must later be stress relieved, but gives the best deposition accuracy with respect to existing geometry. The second method is to kinematically constrain the part such that deflection in the deposition process will not affect the subsequent machining processes. An example of this second method is using 3 points to support a plate substrate during LENS processing and then using the same 3 points to support the part during machining. The plate may bend but it will not affect the machining because of utilizing the same 3 points for the secondary machining.

D. Heat Sinking – When depositing on thin wall structures, it may be necessary to utilize high conductivity heat sinks to prevent the existing geometry from overheating. Heat sinks should conform to the geometry as closely as possible while also being removable in the glovebox if necessary.

E. Process Test Artifacts – It is helpful to create test artifacts that can be used during process development. It is imperative that these artifacts match the repair geometry as closely as possible. It is important to include external features (other than the one being repaired) that may affect heat conduction or powder flow. For example, if depositing material into a hole, it is important to consider whether the hole is in a large block of material, a thin wall, or a boss cantilevered from a thin wall. Though the hole might be exactly the same in these 3 instances, the process parameters will differ considerably due to the heat conduction routes in the part. An example of the need for matching test artifacts is shown in Figure 2.4.A. The process development block had exactly the same hole geometry, but did not have the same surrounding geometry as the real part. When the process parameters used for the process development were applied to the thin wall part, the part was severely discolored due to heat. An aluminum block was used as a heat sink to make the actual geometry match the process development geometry and successful hole filling was completed.
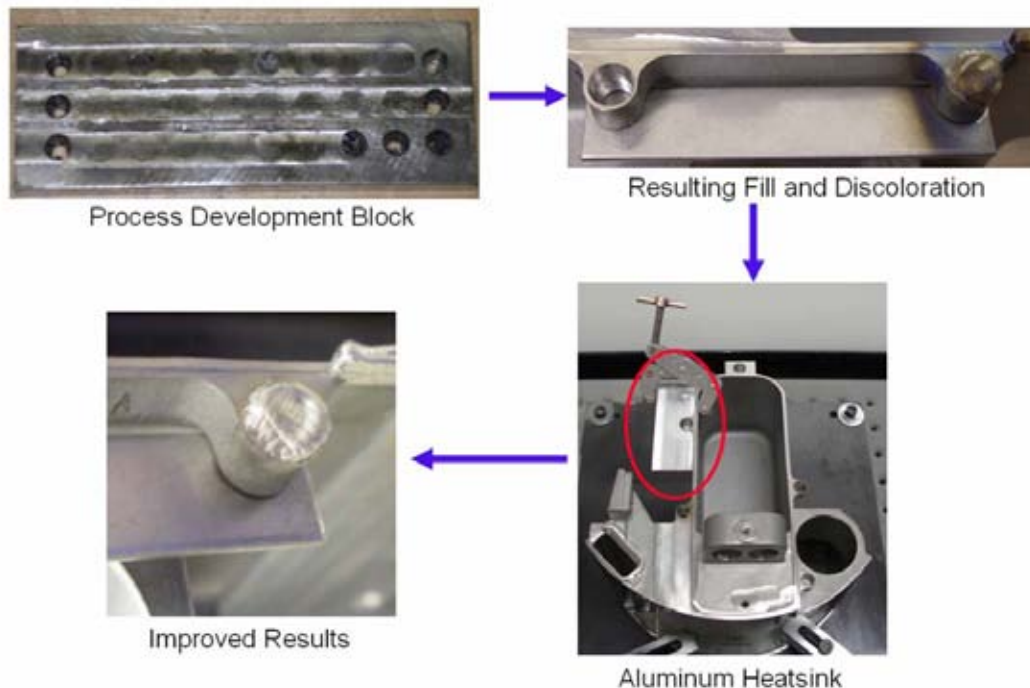
Figure 2.4.A: A Hole Filling Exercise Showed the Importance of Process Development Geometry Matching the Actual Geometry

F. Model Dimensions – Because LENS is a near-net shape process, it is necessary to overbuild the part geometry so that material is available to be machined away to create required machined surfaces. Generally, all surfaces should be offset by 0.020-0.030 inches to leave sufficient material for cleanup machining. When developing new process parameters, it is important to consider the need for overbuilding of the height of the part. A set of process parameters that makes a block that is designed to be 0.5 inches tall

exactly 0.5 inches tall is not building to sufficient height in most cases. An additional 0.020 inches makes the block more amenable to post-process machining.

G. Process Planning Options – LENS process research has shown that the best feature accuracy and microstructure occur when a part is built by creating a border and then filling in the border with overlapping passes or hatch lines. The following layers are all built in the same manner, however the angle of the hatch is rotated 105° from layer to layer to assure optimum deposition characteristics as shown in Figure 2.4.B. However, some feature types, especially thin walls, are better suited to conformal passes that essentially trace the edge of the feature with increasing offset from the edge. Conformal deposition is faster, but has the opportunity to propagate errors from layer to layer and to insufficiently fill the geometry. In this case, it is important to offset each layer by ½ of the offset distance for each layer as shown in Figure 2.4.B (B). This will allow a layer above to fill in-between the hatch lines of a preceding layer. So, when choosing deposition method, 105° hatch is preferable in most situations, but when necessary, conformal deposition can be done as long as layers are offset by ½ of the hatch spacing. Often this choice will be dictated by geometry and possibly by additional concerns such as minimizing heat input. Occasionally the decision will be influenced by the expediency of writing the machine code. The programming of 105° hatch is easily done with a code generator like SNL's Damocles, but in some repair situations where complex geometry or the need to avoid existing geometry do not lend themselves to automatic code generation, it will be much easier to manually program conformal pathways.
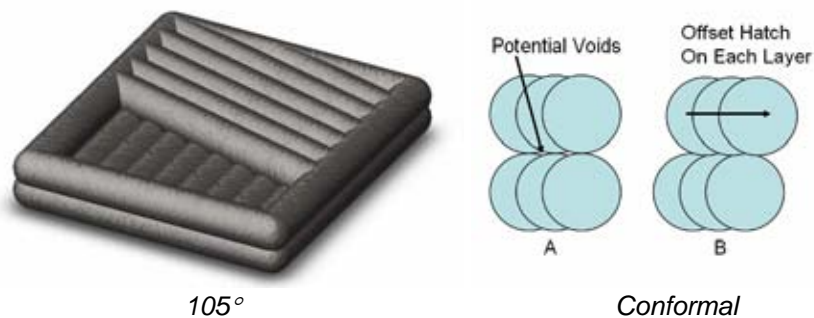
105°   Conformal

Figure 2.4.B: The "Hatch" or Fill Direction of Each Layer is Rotated 105° From The Direction of the Preceding Layer (Left). In Conformal Builds (Right), the Potential for Interlayer Voids (A) is Decreased When The Hatch Lines Are Offset By ½ of the Hatch Spacing from the Previous Layer(B)

H. Order of Operations – The introduction of LENS into a part repair or fabrication process may change the order of operations. The LENS process introduces heat that has the possibility of warping existing geometry or introducing stress into the part. Because of the heat, it may be advantageous to rough machine a part, LENS deposit, and then add a heat treat step before finishing the part. Another example may be the need to leave additional stock to help with heat dissipation during the LENS process or to better balance geometry thicknesses during heat treatment. Then the thickness would be machined away afterwards. And finally, it may be necessary to change the order of some machining or some LENS depositing to allow access of either the machine tool or the LENS nozzle. An example where this approach was necessary is the housing shown in

Figure 4.2.C. The walls and bosses were deposited by LENS onto a conventionally machined dome. Because of heat deformation concerns, the dome was left at a thickness of 0.5" for the LENS and post-LENS heat treatments. The dome was then finish machined to its final part dimensions.
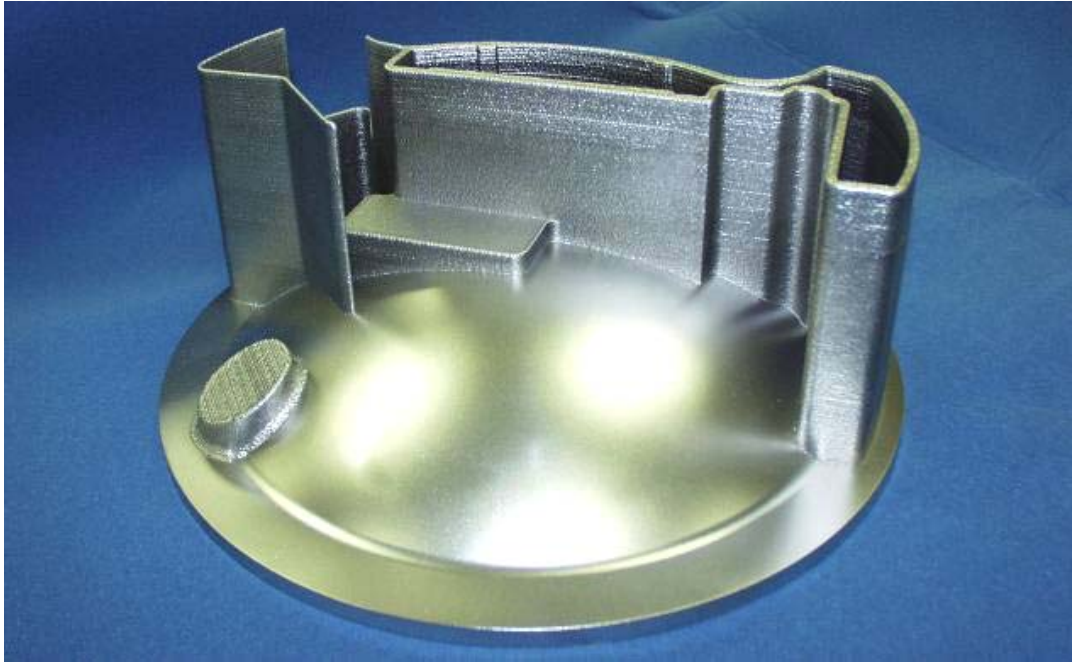
Figure 4.2.C: In Order to LENS Deposit the Walls and Bosses on the Conventionally   Machined Dome Without Causing Undue Warpage, the Dome was Rough Machined and Remained 0.5" Thick Until After LENS Depositing and Heat Treatment. The Dome Was then Machined to Final Thickness.

I. Heat Treatment / Annealing – It may be necessary to perform a post-LENS deposition heat treatment cycle to anneal parts. In general, LENS material will react to heat treatment similarly to wrought material, so industry standard practices can be used on the LENS material. Heat treatment is covered more fully in section 3.2.7.

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3 MATERIALS PERFORMANCE DATA

3.1 Introduction

In order to characterize the process and provide optimal results when using LENS for modifications, repairs, and complete build-ups, extensive testing has been done on LENS deposited materials. Testing has been performed on the following materials: 304L, 316L, and PH 13-8 Mo stainless steels. The baseline material for this study is the 304L stainless steel which was identified early-on as the material of choice for the first two user applications: 1) An L–shaped bracket as a complete "build-up", and 2) A complex housing for a firing set. The applications were for two different LEP projects to modify and upgrade existing NWC systems. Furthermore, 304L stainless steel is used for a wide variety of parts and is used in all NWC systems. 316L is a sister alloy, similar in composition, microstructure and properties, and is also widely used. PH 13-8 Mo is a heat treatable steel, which provides higher mechanical strength for more demanding applications. Its importance relates to opportunities to re-furbish existing firing set housings for safety and security upgrades, without having to scrap out entire parts, and to reduce development time when designers routinely evaluate several rather than a single design option. Not all of the tests described in the following sections have been performed on all materials. However, testing results for LENS applications requiring the use 316L and 13-8 Mo stainless steel can also be found in the following sections.

3.2 Basic Mechanical Properties

3.2.1 Background

Uni-axial tensile testing was the basis for evaluation, and test coupons were sized for making standard R-5 cylindrical threaded tensile bars, similar to those used extensively in evaluation of WR forgings for gas transfer systems.   These samples are small enough to enable sampling from actual parts and/or to obtain coupons at minimum cost and time. Samples were pulled in tension until failure in order to obtain the basic materials properties, and document fracture mode that would be of use in selecting materials of construction and to provide options for refurbishment and performance upgrades. Selected samples were used to determine microstructure associated with the properties and to use that information to establish relationships between processing parameters and performance properties. However, the results reported focus on demonstrating the repeatability of the process rather than the ability to modify microstructure and properties by careful selection of processing parameters. Prior to making parts, process development experiments were carried out to optimize deposit quality, surface finish, and dimensional reproducibility. In addition, it was found that both time and cost could be minimized in the fabrication of actual parts, and as such a small sampling of coupons was used to determine the impact of accelerated build rates on properties, using the facilities of a commercial LENS fabrication shop. Properties are also reported for coupons made by another commercial LENS facility that was used to obtain the initial lot of development brackets.

3.2.2 Tensile Properties

LENS deposited test coupons were 3/8 by 3/8, by 2 inches high, oriented for testing the inter-layer boundary properties. For the repeatability evaluation, thirty test coupons were built in groups of 3 over 12 weeks, using baseline conditions for a constant melt pool size. Cylindrical tensile specimens were rough EDM cut, finish machined on a lathe with a 0.125 diameter and 0.62 inch gauge length. Tensile strain rates were consistent with the ASTM E8 standard. A 0.5 inch extensometer was used to measure elongation, and measurements of the diameter of the gauge section before and after testing were used to determine the reduction in cross sectional area at fracture. The coupons were made over a period of several weeks in between the making of parts for the TIP project to meet other production agency needs. These included machining study blocks, coupons for hydrogen environment testing, and corrosion test coupons. A randomly selected subset of 10 test coupons was used for analysis. Analysis consisted of uni-axial tensile testing, fracture surface analysis and microstructure evaluation. Uni-axial testing was done at a strain rate of 0.05 in/in/min.

Table 3.2.2.A: Tensile Strengths And Ductilities Of 304L Repeatability Samples

Sample	UTS (KSI)	YTS (KSI)	et (%)	RA (%)
TIP 111	102	52	51	38
TIP 122	101	52	54	39
TIP 212	110	65	54	50
TIP 222	106	60	56	51
TIP 613	101	54	69	51
TIP 313	102	59	32	25
TIP 322	103	58	37	27
TIP 412	97	50	58	53
TIP 423	96	50	63	56
TIP 512A	106	64	38	29
AVG	102	56	51	42
STD DEV	4	6	12	12
STD DEV (pct)	4	10	23	28
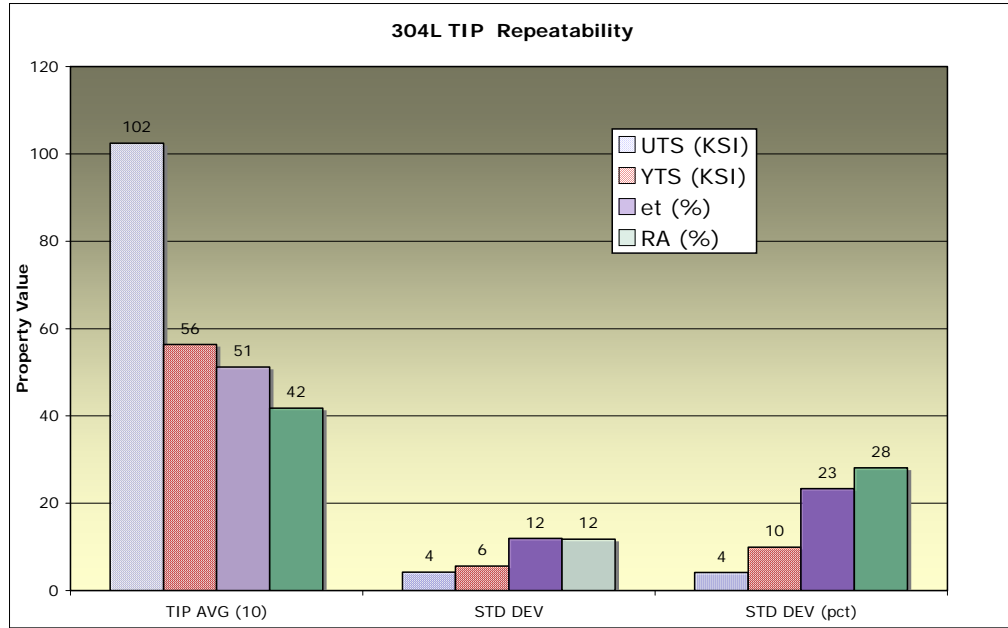
Figure 3.2.2.A: Average properties of repeatability samples.

Table 3.2.2.A lists the tensile properties of the first group of coupons produced to demonstrate the repeatability of the process. Figure 3.2.2.A shows the average properties and their variation. The specification for 304L, ASTM A240, calls for minimums in ultimate tensile strength (UTS) of 70 KSI, yield tensile strength(YTS) of 25KSI, and ductility measured by total elongation (et) of 40%. On average, the repeatability samples had an average UTS of 102 KSI, YTS of 56 KSI, and a total elongation of 51%, well in excess for conventionally processed 304L. As is expected for 304L, when the material has a higher yield strength, there is an associated reduction in total elongation before failure. In a few cases the elongation values observed were below the 40% called out in the specification, but none was lower than 32%. As will be seen below, these samples were produced when the closed loop feedback control was experiencing technical difficulties. Due to loose electrical control connections, a consistent, uniform size melt pool was not maintained during the entire build. This glitch led to the ductility as measured by reduction in area (RA) to have the lower than expected average of 42%.

3.2.3   Fracture Mode

After testing to failure, the fracture surfaces of the broken samples were examined in a SEM to determine fracture mode. Based on the ductility measured on the test samples, the samples fell into two categories: 1) those with 54 to 69% total elongation, and 2) those with 32 to 38% total elongation.   Samples with the higher ductility exhibited classic cup-cone ductile fracture., as shown in Figure 3.2.3.A.
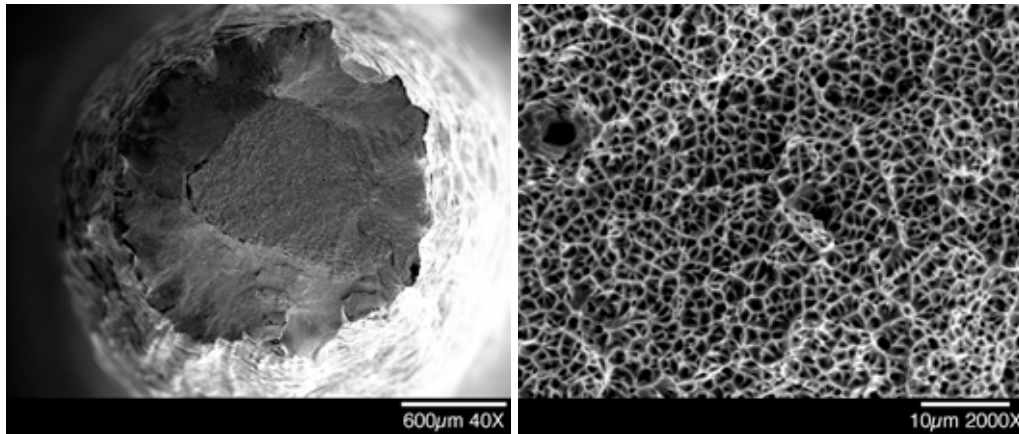
Figure 3.2.3.A: Typical fracture surface of samples, with 54 to 69% total elongation, showing classic cup-cone characteristics (left), and ductile dimpled fracture (right).

Samples with the lower ductility exhibited premature fracture., as shown in Figure 3.2.3.B(a). These were not considered typical, and were traced to anomalies in the behavior of the melt pool size controller. As can be seen from the micrograph, delamination of the layers occurred. Despite this flaw, surrounding evidence confirms that the fracture is otherwise ductile as seen in Figure 3.2.3.B(b)
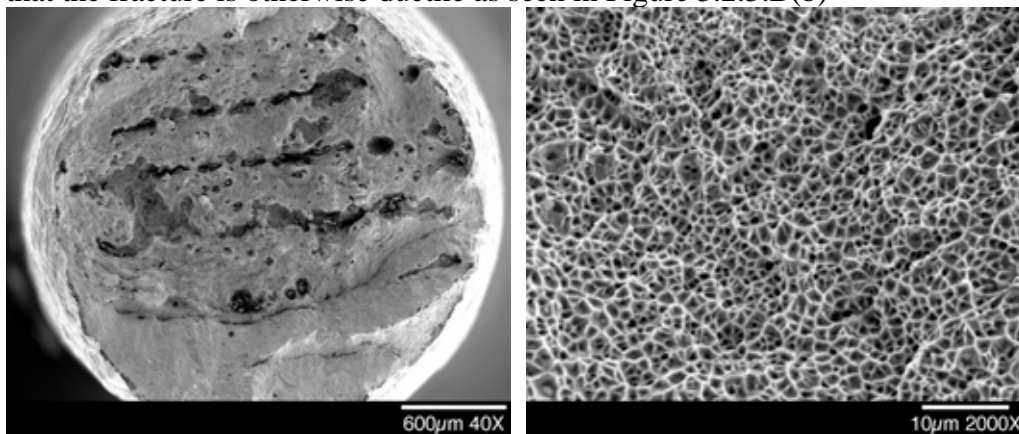
Figure 3.2.3.B: Fracture surface of samples, with 32 to 38% total elongation, showing premature fracture at interlayer defects (left (a)), despite having ductile dimples fracture characteristics (right (b)).

3.2.4   Microstructure Characteristics

An evaluation of the microstructures of the two groups of samples was initiated to determine if there was a correlation between behavior and the microstructure. Metallographic samples were sectioned perpendicular to deposition direction of top layer. Standard rough grinding, followed by polishing, was used to evaluate the extent of porosity. Etching was done to evaluate melt pool characteristics. Since each successive layer is deposited in a direction 105˚ from the previous layer, the top layer represents a look at the cross section of the melt pool size and the extent of overlap of successive line scans. Layer thickness, width, and height of top deposition layer were evaluated. The typical structure consists of nearly uniform sized semi-circular melt pool

cross-sections as shown in Figure 3.2.4.A. It is seen that the width and height of the melt pool is reasonably uniform for samples with 54 to 69% total elongation. This indicates that the melt pool sensor and closed loop feedback control does keep the deposition conditions relatively stable and therefore constant solidification conditions over the course of the sample builds. Note that the top layer indicates a height to width ratio > 1, with the height considerably greater than the setting for increments in heights from one layer to another.
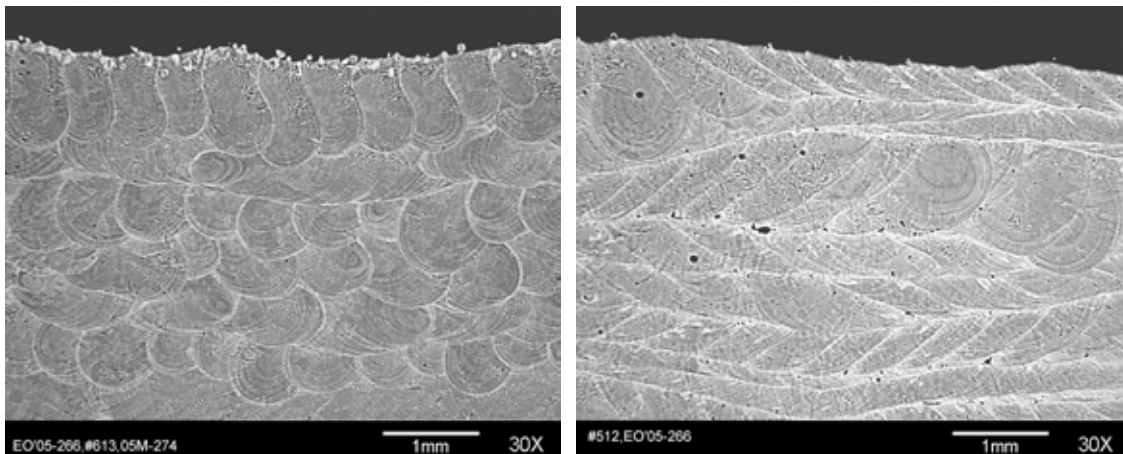
Figure 3.2.4.A: Microstructure of the 54 to 69% total elongation samples (left), showing that the melt pool size is reasonably uniform over the sample cross-section, while the microstructure of samples with 32 to 38% total elongation (right), is very non-uniform.

Examination of the build log, and operation of the melt pool controller, revealed erratic fluctuations in the current to the laser. It was determined that several wire connections had become loose and once re-tightened, the erratic fluctuations were eliminated. Procedures for insuring the integrity of all electrical connections have been instituted to eliminate the anomaly. It was concluded that the 54 to 69% total elongation is typical for LENS processed 304L, and that the strength and ductility, measured by elongation, exceed those specified for annealed conventionally processed bar stock. Microstructure suggests that variations in the thickness of the deposited layer caused premature failure for low ductility samples.

3.2.5   Hydrogen Compatibility

A challenge to the successful qualification and acceptance of LENS® processed materials for service in hydrogen isotope applications is the ability to demonstrate that the mechanical properties are at least comparable to conventional materials. As such, the focal point of this task was to evaluate the tensile properties—including yield strength, ultimate tensile strength, and elongation to failure—of LENS® materials in both the uncharged and hydrogen charged conditions. No attempt will be made to compare to forged, pedigreed gas transfer bottle materials. Sub-miniature tensile dogbone samples were harvested from an 8 cm^3 block of 304L LENS® materials prepared by SNL. The samples were harvested using EDM at SRNL. Companion samples were harvested from 0.020 inch thick 304L commercial sheet stock material.

The tensile dogbone samples had a 0.5 inch gauge length and an overall sample length of 1.25 inches. The tests were conducted on samples charged for 14 days at 4250 psig H_2 at 350 °C. Testing was performed at room temperature in air using a screw-driven testing machine with pneumatic grips and a crosshead speed of 0.002 in/min. The load was measured by the load cell on the machine, and the gage length displacement was measured with a clip gauge attached directly to the sample.

In addition to this mechanical testing, small sample punch tests were performed to compare the fracture toughness behavior of hydrogen charged with uncharged LENS® processed 304L material. This technique is amenable to small sample sizes and the experimental set-up is rather simple. Tests are conducted on samples approximately 3mm in diameter and 0.5-0.75 mm in thickness. A load is placed on the disk sample via the tensile load frame cross-head pushing on the punch rod of the test apparatus. Typical crosshead speeds of 0.1-0.2 mm/min are employed. As a relative measure of fracture toughness several empirical relations have been developed in the literature. Using the original sample thickness and the deflection at sample failure the biaxial fracture strain is calculated. Using this calculated biaxial fracture strain and an empirically determined relationship between biaxial fracture strain and measured ductile fracture toughness K_{IC} values can be estimated. Punch test samples were harvested from an 8 cm^3 block of 304L LENS materials prepared by SNL. The samples were harvested using EDM similarly to the tensile samples discussed above. The punch samples were approximately 0.040 inches in diameter and 0.010 inches in thickness. The tests were conducted on samples charged for 14 days at 4250 psig H_2 at 350° temperature. Testing was performed at room temperature in air using a screw-driven testing machine with a 1 mm diameter tungsten carbide ball at a crosshead speed of 0.008 in/min while recording load and crosshead displacement via a gauge attached to the compression platen.

The tensile curves results showed that for both the longitudinal and transverse sample direction (longitudinal and transverse to the build direction of the 8cm^3 block) there is little difference in the yield strength and ultimate tensile strength comparing identically oriented samples exposed to hydrogen to those not exposed. The largest difference between the unexposed and exposed samples occurs with respect to the percent elongation to failure (%EL). The %EL in both orientations decreased following exposure of the materials to hydrogen. This indicates the reduced ductility from hydrogen embrittlement which would manifest itself potentially in reduced fracture toughness.

Analysis of the small sample punch test data to estimate the reduction in fracture toughness of the LENS process 304L material upon exposure to hydrogen was also performed. Calculation of the biaxial fracture strain ε_{qf} in both the longitudinal and transverse direction shows that the estimated strain at fracture for both directions upon exposure to hydrogen decreases on the order of 50%. Examination of the trend for the estimated ductile fracture toughness values shows that hydrogen exposure decreases the fracture toughness and that the transverse orientation appears to be more susceptible.

A copy of the full report is attached in Appendix A.

3.2.6 Corrosion Resistance

Stainless steels are typically chosen for an application due to their corrosion resistant properties. The corrosion resistant properties are primarily due to the presence of chromium, which forms a stable chromium-rich oxide layer on the surface of the metal. If stainless steel is exposed to temperatures in the range of 600ºC to 900ºC (1100ºF to 1650ºF) a process called sensitization may occur, which promotes the precipitation of chromium carbides at the grain boundaries. This causes chromium depletion zones in the metal matrix inhibiting the formation of the protective oxide layer reducing its corrosion resistance. This type of corrosion is known as inter-granular corrosion and can be caused by welding or other processes that introduces heat in the sensitizing range. The sensitizing temperature range does not usually occur at the actual weld but typically in the metal next to the weld called the Heat Affected Zone (HAZ). At the actual weld the heat is above the sensitizing range and cools quickly. Failures due to corrosion typically fail in the HAZ.

LENS is a laser deposition process that can be used to either build new parts or repair existing parts. If used to repair an existing part the LENS process will introduce heat into the part similar to that of welding processes producing a HAZ. An advantage for the LENS process is that it uses a laser which gives highly concentrated heat input, resulting in a small HAZ. This study investigated the corrosion properties of the LENS material and the HAZ on the base material of a simulated repair. 304L and 316L stainless steels were used in this investigation. Coupons of each material were made by LENS depositing the respective material onto 1 inch by 1 inch square conventional 304L and 316L stainless steel blocks. After the deposition the coupons measured approximately 2.5 inches in height and were made of half conventional stainless steel and half LENS deposited stainless steel. The coupons were sectioned into three different samples types that included LENS, conventional, and a 50/50 mix of both that included the HAZ. The samples were then left in this condition or underwent either of two sensitizing heat treatments at 675ºC (1250ºF) for 1 hour or 20 minutes. The two heat treatments are for carbide precipitation and are required for testing of extra-low-carbon grade stainless steels.

Corrosion tests included ASTM A262 Practice A and C for detecting susceptibility to inter-granular attack in stainless steels and Potentiodynamic Anodic Polarization tests to determine passivity behavior and corrosion rates. ASTM A262 Practice A is an oxalic acid etch test for classification of etch structures of austenitic stainless steels. ASTM A262 Practice C is a nitric acid test for detecting susceptibility to inter-granular attack in austenitic stainless steels, which uses a loss-weight calculation to determine corrosion rates. Potentiodynamic Anodic Polarization tests are generally used to produce a qualitative picture or "fingerprint" of a substance in a given solution. It also detects any tendency of the substance to form a passive film, which stops or significantly reduces corrosion.

The test results of this study showed that the LENS deposited stainless steel and HAZ of the coupon exhibited corrosion properties as good as or better than the conventionally processed metal. The only case in which the LENS material had a higher corrosion rate was when a large amount of porosity was present. All 304L and 316L LENS samples and 50/50 mix samples passed the ASTM A262 Practice A tests showing no gross chromium carbide precipitation at the grain boundaries. The 304L LENS samples in all conditions had a lower corrosion rate than the conventional 304L sample and the 50/50 mix sample had a comparable corrosion rate in the ASTM A262 Practice C test. In the same test some of the LENS 316L samples had a higher corrosion rate than the conventional metal due to an appreciable amount of porosity. The Potentiodynamic Anodic Polarization test showed that the 304L and 316L LENS material and the 50/50 mix samples formed a similar protective passive film to the conventional stainless steel increasing corrosion resistance.

The entire report on the corrosion properties of LENS deposited 304L and 316L can be found in Appendix B.

3.2.7   Heat Treatment Effects

Residual stress is inevitable in any type of metal processing. LENS is a type of metal processing that can be used to build near net shape parts or to add metal to pre-existing structures. Theoretically, LENS should introduce lower amounts of stress when compared to current industry practices used to repair parts, such as tungsten inert gas (TIG) welding. LENS uses a CNC controlled laser as it deposits material, and imparts less heat on the substrate, which leads to the heat affected zone (HAZ) being smaller than that of TIG welding. Since the process is more precise, small additions of material can be added to make repairs, which is an advantage over previous industry methods. This study focuses on both determining the degree of stress induced by the LENS process and how to eliminate those stresses via heat treatment.

A ring structure was chosen as a suitable shape that would have a measurable physical effect from stress. All rings were constructed with LENS and consisted of a two inch outside diameter and half inch length. Two parameters were chosen for the experiment. The first parameter, wall thickness, was chosen with the walls of the W87 Firing Set Housing in mind (0.070in., 0.120in., and 0.180in.). The second parameter was the deposition pattern. Two different deposition patterns where chosen to simulate common industry practices. One was a linear or circular side by side pattern used for thin wall builds, and the other was a 105 degree hatching pattern, which is more commonly used. While initial intentions were to create samples of both depositions for each wall thickness, current LENS depositing and programming capabilities would not allow this, and modifications from the original scope had to be made. Three thermal cycles were used to compare and evaluate the amounts of stress relieved in the ring structures. Furthermore, since the material is built on a substrate it is thought that the stresses introduced might be different at the base when compared to the open end of the build. This effect was also studied.

The study found that common industry standards for wrought 304L stainless steel heat treatments are applicable to LENS builds. In addition, thin wall LENS structures, which are deposited using linear deposition, contain larger amounts of stress than thick wall structures deposited via the 105 degree hatch method. It was also observed that LENS material nearest the substrate contained less stress than LENS material of the same build (rings were cut from seven inch long tubes) located further from the substrate. The LENS team theorized that this could be due to the substrate acting as a heat sink which pulls the stress inducing heat out of the part more quickly.

The entire report regarding stress location within LENS builds as well as a discussion on using thermal cycles to relieve stress found in 304L LENS material can be found in Appendix C.

3.2.8   LENS Processing

The LENS process differs from traditional machining processes because the material's microstructure is created at the same time as the geometry. S,o process parameters affect not only the accuracy of features but also their strength, ductility, porosity, etc. The LENS process has many process parameters which can be adjusted to optimize the build, but there are 4 parameters that are of greater significance than the others, having greater impact on the build. The parameters are listed along with a description of their effects, interactions, and the means by which that parameter can be adjusted.

A. Laser Power – The laser power determines the amount of energy that is put into the melt pool. Power that is too low will not sufficiently melt the incoming powder which leads to particle inclusions and short build heights. Power levels that are too high may ablate the material or introduce so much heat that the cooling rate of the material decreases thus losing the grain refinement possible with LENS. When the power input is too high the melt pool grows and the surrounding areas are also extremely hot. Sometimes powder particles will adhere to the outside of the part due to the high heat. These particles often cause problems later in the process.

Interactions with the laser power include the axis feedrate and the embed value. If the axis feedrate is too slow, the cooling rate is reduced and the required power will be lower. The embed value determines the diameter of the weld pool. As the diameter increases, the power necessary to maintain such a large weld pool is also increased. This dependence on irradiance, the incident power per unit area, must always be considered as the parameters are changed.

Power is primarily controlled by adjusting the current provided to the laser cavities by the laser amplifiers. The laser power must be mapped with respect to laser current as the curve is not linear and changes as the laser flash lamps age. An example laser power plot is shown in Figure 3.2.8.A. It is important to measure the laser power below the nozzle as there are power losses through the system optics and the losses are somewhat nonlinear with increasing power.
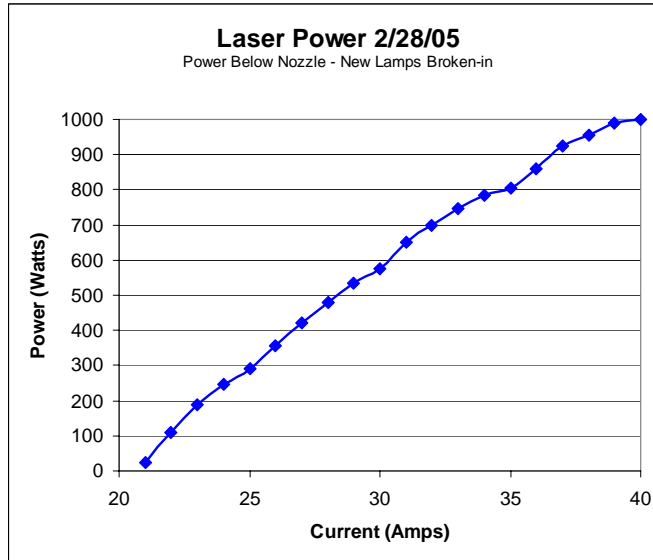
Figure 3.2.8.A: Laser Power Measured as a Function of Input Current. The Curve Changes Over Time As the Laser Flash Lamps Age

As mentioned previously, the laser power is important, but the irradiance or power incident per area is more significant to the process. Because of this dependence and because of variability of the highly dynamic melt pool, Sandia National Laboratories' LENS system is controlled by a closed loop melt pool area control (MPAC) system. This system monitors the area of the melt pool that is above a certain intensity which is material dependent. The system then raises and lowers a control voltage that in turn varies the current in the laser amplifiers and thus the laser power. By this means, the irradiance is kept as nearly constant as possible. In the MPAC system developed by Sandia National Laboratories and William Hofmeister of Vanderbilt University, there are two means of adjusting the desired power imparted on the melt pool. The control screen is shown in Figure 3.2.8.B. The first method of controlling the melt pool is the Threshold Intensity value. This value sets the threshold intensity that the system uses to calculate the area of the melt pool. The second control is the Fill, Border, and Overhang Area values (measured in pixels). These values set the desired area that is to be above the chosen intensity. There are 3 different values used as the desired area is often different for border vs. hatch lines. Additionally, border that is supported often requires a different value than border that is overhanging or unsupported to some extent. So, the laser power is increased if the user either increases the desired intensity or increases the desired melt pool area. The desired threshold intensity is determined by mapping the melt pool intensities and determining the liquidus-solidus interface and designating that value as the desired intensity. The area values are then adjusted to produce the desired material properties and geometry for the material, substrate, and build conditions. This is most often an iterative experimental process.
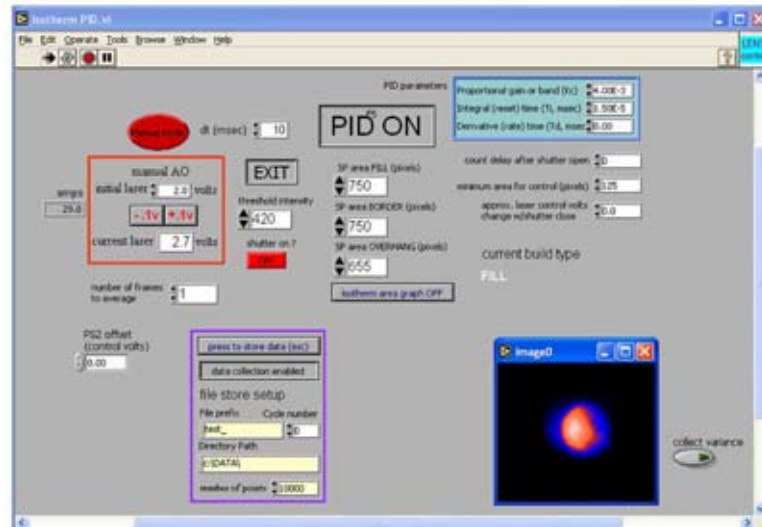
Figure 3.2.8.B: Melt Pool Area Control System Showing Threshold Intensity and SP Area Values That All Affect the Laser Power and Melt Pool Size

There is one other significant adjustment that can be made to the MPAC system. The CCD camera that images the melt pool saturates if the melt pool intensity is too high. To prevent saturation, a neutral density filter is installed inline with the camera to reduce the intensity of the radiation incident on the CCD array. The filter must be adjusted for different materials. Some materials, such as PH 13-8 Mo and especially Ti-6-4 have extremely bright weld pools with high emissivity and require strong filters to prevent saturation. Materials such as 304L and 316L have much less emissive weld pools and do not require as strong a filter. The method of choosing a filter is to find the filter with the least percentage of signal blocked while still eliminating the saturation in the CCD image.

B. Powder Mass Flowrate – The mass flow rate of the powder directed at the melt pool primarily affects the height of the build. Builds in which the melt pool is "starved" will typically create small features and conversely high powder flow rates create builds that look "doughy" or thick and oversize. Examples of cubes with good and bad process conditions are shown in Figure 3.2.8.C. The powder flow rate can also affect how quickly the melt pool cools as the incoming powder has the ability to quench the weld pool such that the incoming powder is not fully melted. This results in inclusions in material and subsequent reduction in interlayer strength. Studies have shown that greatly increasing the amount of powder in the meltpool causes the number of small porosity voids (1-5μm pores) to increase, although it simultaneously decreases the number of larger pores (6-15μm). In the middle of this continuum, there is an optimum where the overall number of voids is insignificant, being less than 0.07% of the material's area. See the interface document in the Appendix I for more information.
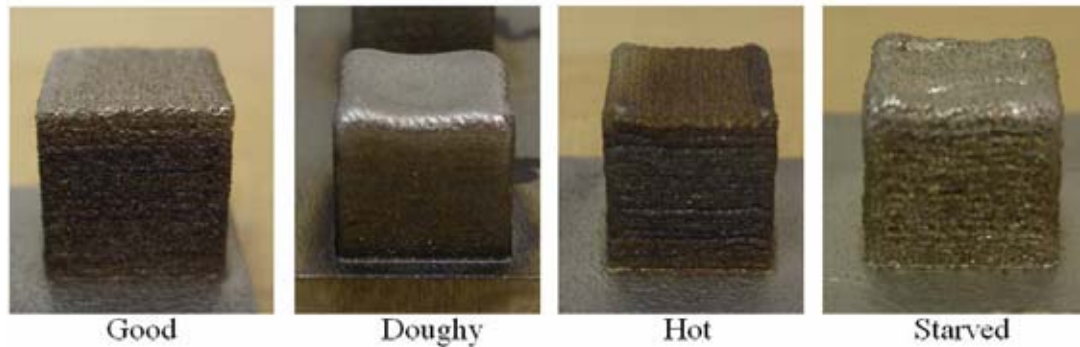
Figure 3.2.8.C: Process Test Cubes (½ x ½ x ½") Showing The Effects of Different Processing Conditions

The mass flowrate of the powder is controlled by increasing or decreasing the powder metering rate of the powder feeder. While the flowrate could also be controlled by changing the velocity of the incoming powder and argon stream, that is not usually an effective means of controlling the feedrate due to other complicating factors. There is a swirl of gasses from the different feeder nozzles around the melt pool as well as axially flowing gas that protects the focusing optics from stray hot particles. Because of this swirl of gas, the particles must be given sufficient momentum that they maintain their trajectory from the nozzle tip to the melt pool. Because of limitations on the mass of the particles that work well in the LENS process, the momentum is maintained by having sufficient velocity of the particles. Thus powder mass flowrate is controlled separately through the rate at which powder is fed into the argon stream.

The powder mass flowrate has interactions with the axis feedrate and with the embed value. It is desired that a certain amount of powder be entrained in the melt pool. If the axis is moving slowly, then the powder mass flowrate does not have to be as high to get the same amount of powder into the melt pool. The embed value adjusts the amount that the focal point of the laser is embedded into the part, thus adjusting both the relative position of the powder cone with respect to the laser focal point and also the diameter of the melt pool. If the melt pool is larger, it is easier to entrain powder in the melt pool. If the melt pool is small, a large percentage of the incoming powder hits the unmelted area around the melt pool and falls away, not becoming entrained in the melt pool and not contributing to the part building process.

C. Axis Feedrate – The axis feedrate determines the speed at which the incident laser power and resulting melt pool is moved along the surface of the substrate. As the feedrate increases the cooling rate of the melt pool increases and the overall temperature of the surrounding part decreases. A higher cooling rate causes the grain structure to become more refined which leads to higher strength, usually with only a small loss in ductility. It is important to note that while the grain size is quite small after one pass, the subsequent 10 layers will heat the material sufficiently to cause grain growth somewhat reducing strength and possibly affecting the part

ductility as well. The axis feedrate also has an effect on the height of the build by increasing or decreasing the amount of time that is available for the powder to be entrained in the melt pool at any specific point.

The axis feedrate is controlled by the programmed speed in the M&G code as well as the Manual Feed Override (MFO) which increases or decreases the commanded axis velocities by chosen percentages. Interactions of the axis feedrate include the laser power and mass flowrate as detailed above.

D. Embed / Focal Point – The embed value is the depth to which the focal point is below the surface of the current build. The focal point is embedded into the material to prevent ablation of the material and to increase the diameter of the melt pool so that build rate is increased. The amount of embed affects the diameter of the melt pool and also affects the amount of intermixing between the current layer and the previous layers. The embed value is distinct from the focus point of the powder cone, so the embed value also can have an affect on the amount of powder that becomes entrained in the melt pool.

The embed value is adjusted by moving the focusing lens up and down with respect to the Z axis and therefore with respect to the nozzle, the start position, and the powder cone. The focusing lens is mounted in a threaded mount which moves 0.050in. per revolution, so adjustments have historically been made in 0.050in. increments. Typical values for embed are 0.175-0.225in. and are material dependent and sometimes geometry dependent as well.

3.3 Weldability

3.3.1   Reclamation Welds

Reclamation test bases were machined from WR-like material. These test bases were fabricated with center bore diameters that exceeded the design tolerance by 0, 0.015, 0.030, and 0.045 inch. Three samples of each bore diameter were fabricated. The samples were sent to SNL-NM for LENS® repair where material to adequately fill the internal bore was added. The LENS® repair was made by canting the disk at approximately a 45˚ angle and filling the bore by rotating the test base. This resulted in a large build-up of material in the center of the test base. The test bases were then machined to nominal dimensions using conventional methods.

Reclamation welds were made using the nominal weld parameters for LF-7 type test bases, i.e., 2250 lbs, 11,400 A, and 25 cycles. All of the welds were consistent with the production weld parameter range. There is a small amount of heat banding and some material extrusion around the weld. These features are typical of reclamation welds

The reclamation test base that was overbored by 0.045 inch was selected for metallography after burst testing. The presence of flow lines in the LENS® material is less apparent than for the fill stem bare stock. There was also some evidence of the presence of fine porosity in the "corner" of the reclamation test base/LENS® material.

The LENS® material seems to have machined well as there is no indication of smearing on the chamfer at the bore centerline.

A copy of the full report is located in Appendix A.

3.3.2   Housings

A view of a polished cross section of a 304L stainless steel plate which was welded to the LENS can lip of the W87 Firing Set Housing can be seen in Figure 3.3.2.A. This weld exhibited a nice rolled edge on the inside edge of the can. This is expected in a laser welding process on such a thin wall. In addition, the weld bead was centered more towards the LENS side of the weld, which rolled the edge. The penetration on this weld was .049".
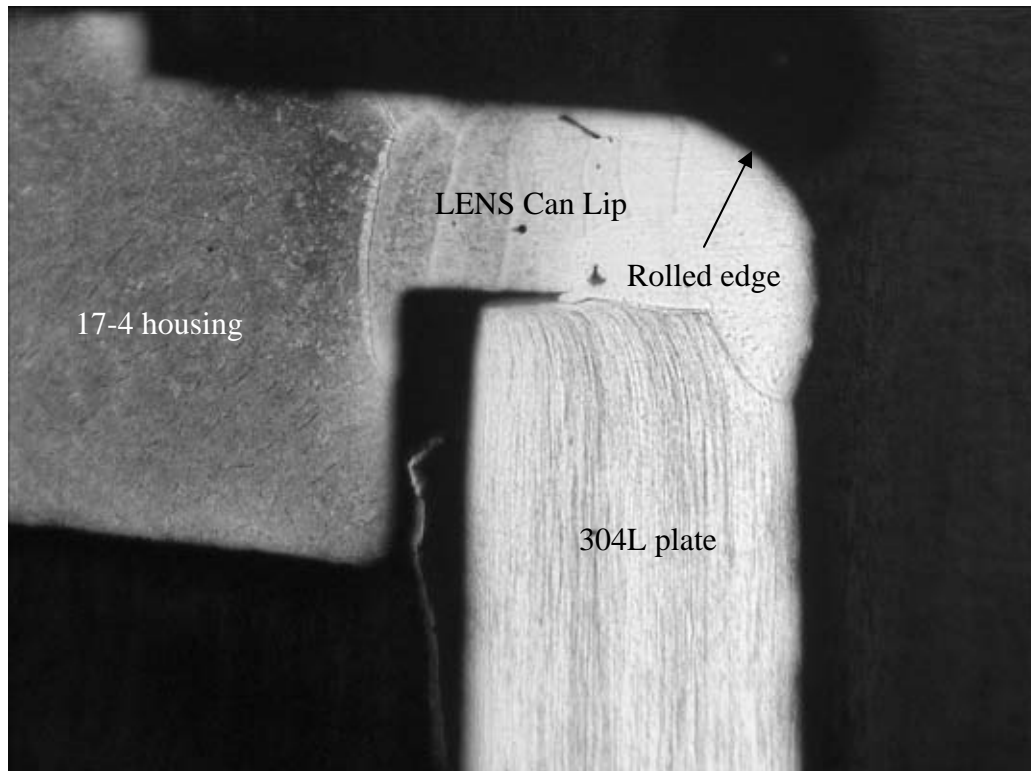
Figure 3.3.2.B: Weld Section 1 (25X magnification with oxalic etch)

Solidification lines of the weld are typical of that of laser welding. There is one void in the weld, which is typical of the laser welding process. The void shown in Figure 3.3.2.B measures .0026" wide and .0022" tall. There is also a large void in the LENS material that measures .0016" wide by .008" length. If this void had been closer to the top of the can lip, it would have most likely affected the weld. This void appears in the overlap of the LENS deposition passes. Had the deposition parameters been optimized for this repair, this void would not have been present. The smaller void in the middle of the LENS material measures about .001" in diameter, and can also be eliminated with further process optimization.
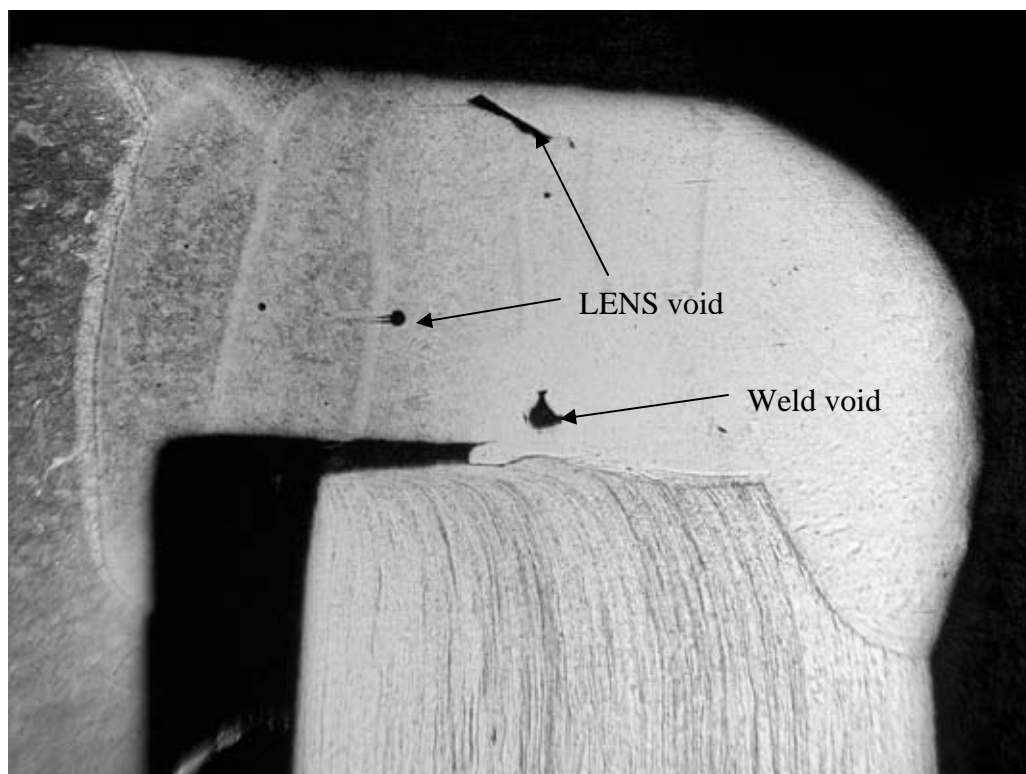
Figure 3.3.2.B: Weld Section 1 (50X magnification with oxalic etch)

Kansas City Plant welding engineers who examined the weld found nothing concerning in the weld itself. There were no detrimental secondary or tertiary phase formations and the weld bond between the LENS material and the 304L stainless steel plate looked good. See Figure 3.3.2.C for a view of the weld at 500X magnification.

The complete weld evaluation study on the W87 Firing Set Housing can be found in Appendix D.
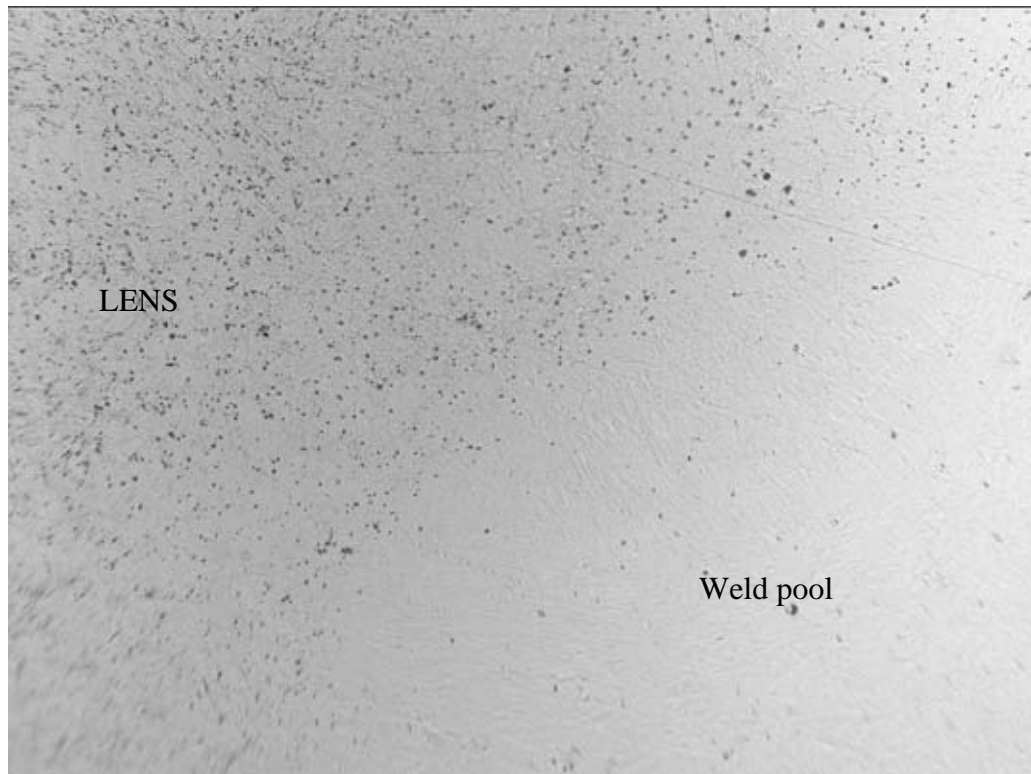
Figure 3.3.2.C: Weld Section 1 (500X magnification with oxalic etch)

3.4 Machinability

3.4.1   Housings

Cover Weld Flange Machining

The cover weld flange and 91.6 radius surfaces (see Figures 3.4.1.A and 3.4.1.B) were machined back to their original design using tooling and work holding fixtures exactly like that used on real WR parts. After the parts were machined they were immediately dimensionally inspected using Kansas City's Department 021 coordinate measuring machine. This was done to minimize the measurement repeatability error which could arise when the parts are taken on and off the work holding fixture. This ensures that measurement error due to part location on the datum pins does not factor into the dimensional inspection. In total, two parts passed dimensional inspection of the cover weld (S/N's 2058 and 2073). S/N 2066 had one point fall out (.00015" plus material) but could have been reworked if need be to pass dimensional inspection. Although the edges of the cover weld flange appear to be jagged and sharp, they do in fact meet minimum opening print requirements (see Figure 3.4.1.C).

Figure 3.4.1.A: View of Cover Weld Flange after Machining

91.6 mm radius surface
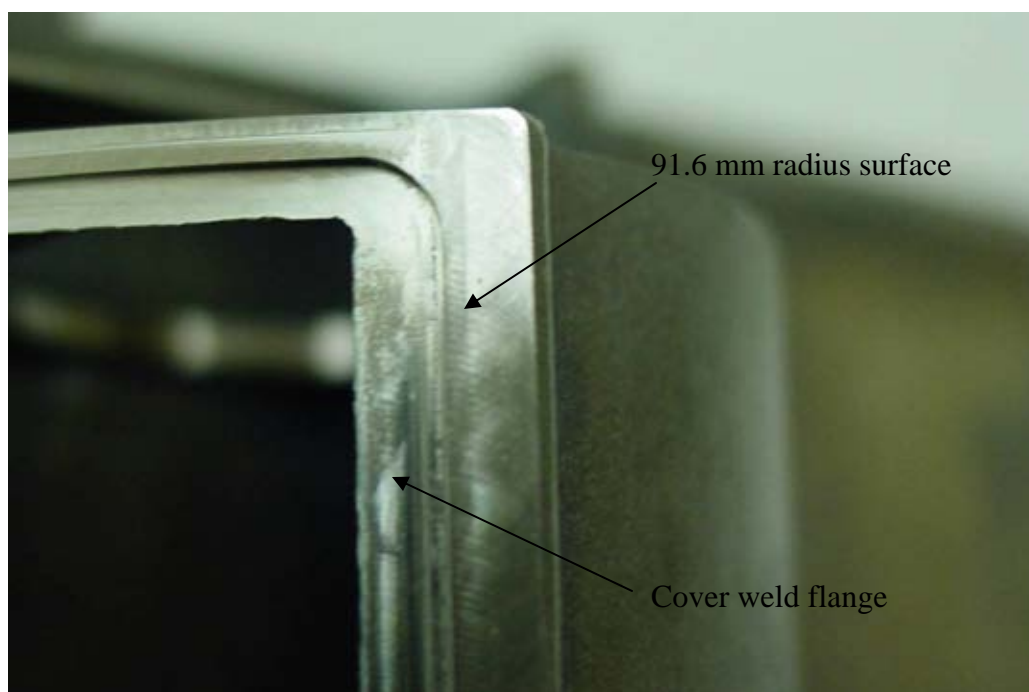
Cover weld flange

Figure 3.4.1.B: Close-up View of Cover Weld Flange after Machining
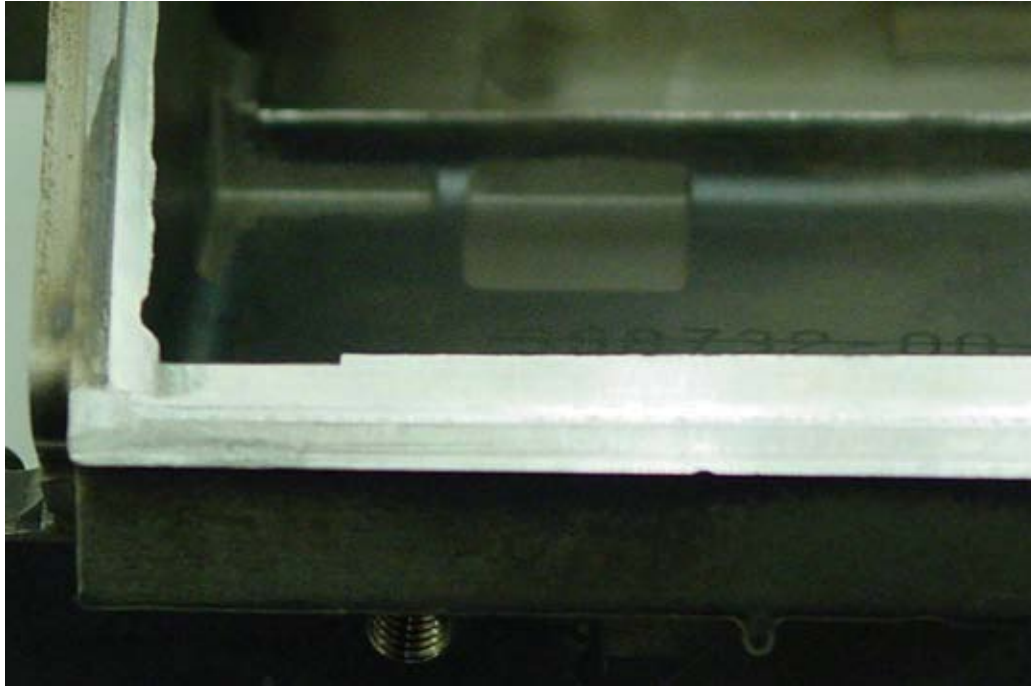
Figure 3.4.1.C: View of jagged edge of cover weld flange – meets minimum requirements

One concern raised during machining centered on how closely the cover weld flange could be matched up with the 91.6 radius surface. The 91.6 radius surface did not have LENS material applied to it, and as such, the NC program would not be able to re-cut both features at the same time. This would have allowed the step depth of .81 millimeters between the two features to be controlled by the NC program. The machining program was subsequently set up to cut the cover weld flange independently of the 91.6 radius in an attempt to minimize a mismatch between the two surfaces.

The parts were machined and no concerning mismatches were noted. The original 91.6 radius matches within .0002" of the newly machined 91.6 radius (see Figure 3.4.1.D). However, should this technique be performed for repair of product in the future, it is suggested to have the responsible engineer specify a distance on the 91.6 radius surface in which to apply LENS material, which could then be machined back to original size while machining the cover weld flange, which would eliminate mismatch and allow the step depth to be CNC controlled. The other alternative, if material permitted, would be to machine the 91.6 radius surface slightly under nominal size during the machining of the cover weld flange. This could prove to be tricky if the radius feature was already under nominal size before the repair. This type of part machining methodology would need to be considered before the LENS repair is made to ensure adequate material exists for the type of repair being performed.

LENS material,
91.6 mm radius
mismatch
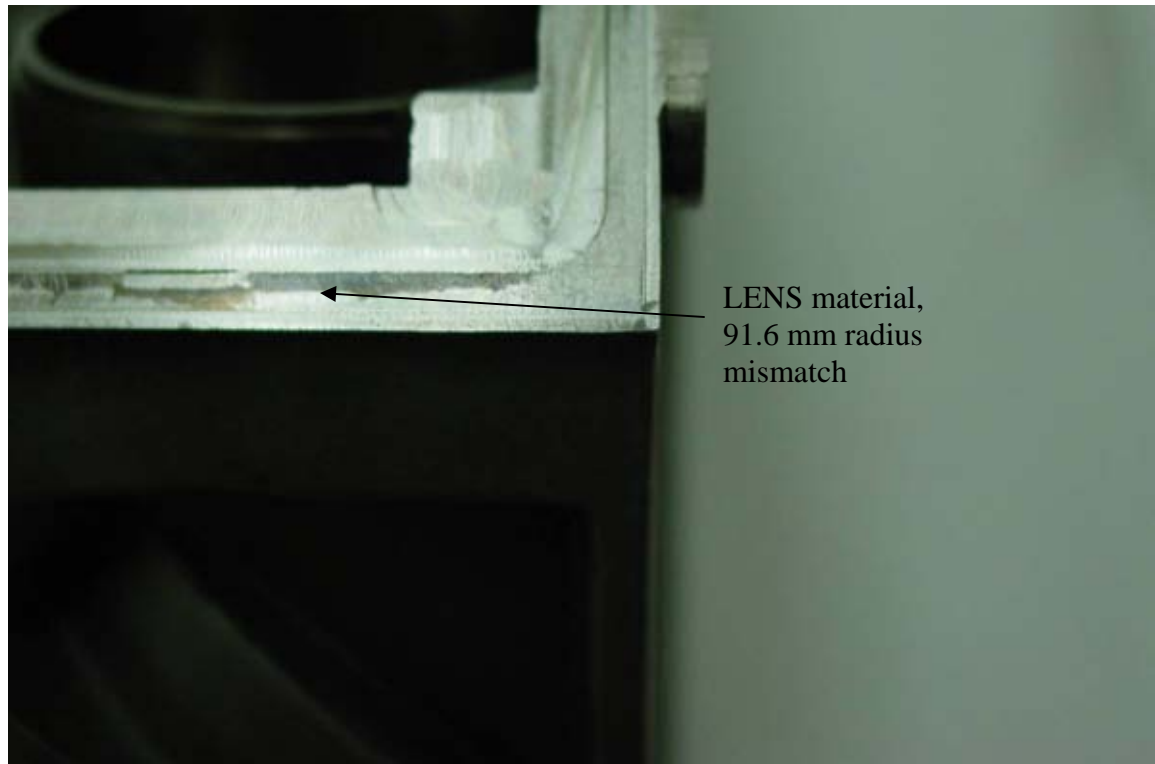
Figure 3.4.1.D: View of Upper and Lower Weld Flange Showing Mismatch

Can Lip and Thread Machining
Following the machining of the weld cover, the can lip and threaded hole features were machined. The can lip feature was difficult to machine to nominal size due to the fact that the casting itself was out of tolerance on the can pocket. This out of tolerance condition is one of the reasons the housings were able to be obtained for the repair, and thus it proved to be difficult to match up a nominally machined can lip with a varying can pocket. None the less, the programmer and process engineer who support the Flexible Manufacturing System where these castings are machined did a nice job of machining the parts back to size. There are a few areas where the LENS material did not clean up entirely, but that is due to the pre-existing warped condition on the can pocket. In future repairs, more LENS material would be applied to account for this, or a part probing feature could be added to the CNC program that would allow the program to derive a best fit for machining the can lip to the pocket while still maintaining contour and minimum wall thickness requirements. See Figures 3.4.1.E and 3.4.1.F for views of the machined can lip.

Can lip

Can Pocket

Figure 3.4.1.E: Can lip after machining

Un-machined LENS surface due to out of tolerance condition of can pocket
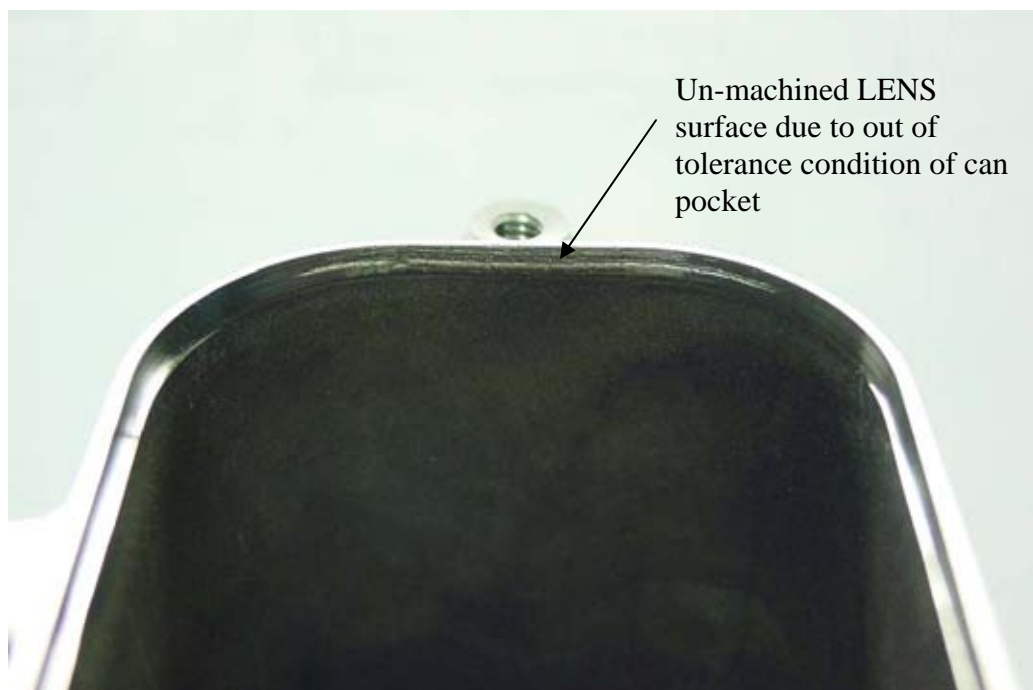
Figure 3.4.1.F: Can lip after machining – could not obtain 100% LENS cleanup

The LENS repaired holes were first drilled to the minor diameter of the threads. The threads were then machined using a CNC thread milling cycle to within .003" of final size. The threads were then hand tapped to their final size. Two holes on serial S/N 2058 were actually hand tapped without first being thread milled. Remarkably, the operator was able to perform this task without breaking a tap. The other LENS filled hole on S/N 2058 was left un-threaded, in order to provide a view of the void which remained inside the hole. See Figure 3.4.1.G for a view of the LENS repaired threads.

A complete evaluation regarding the machining of the LENS material deposited onto the W87 Firing Set Housing can be found in Appendix D.
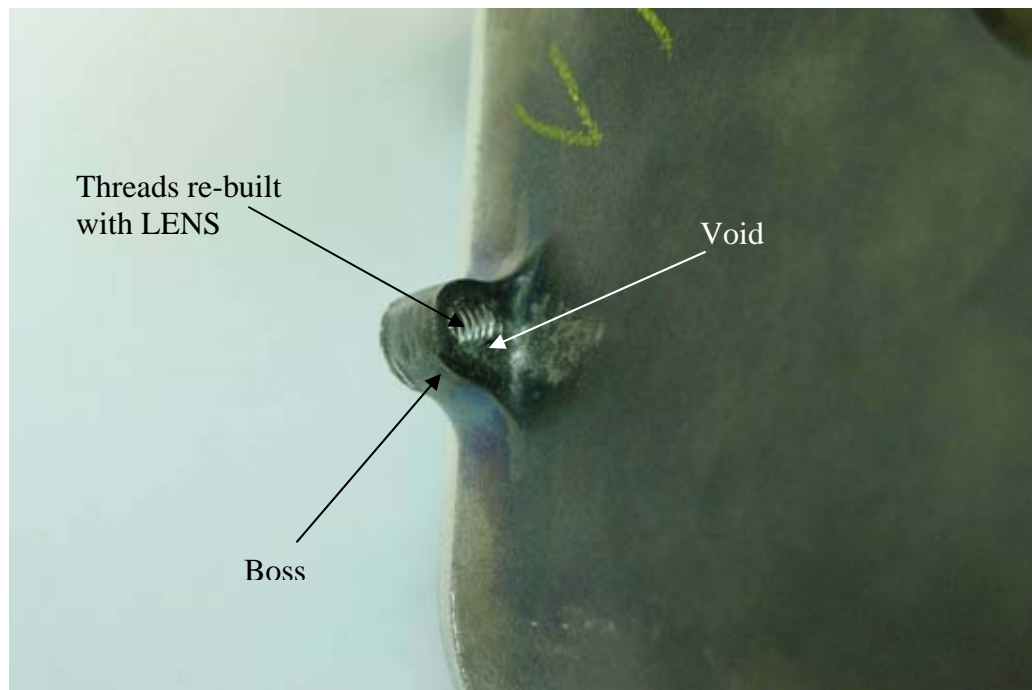
Figure 3.4.1.G: View of underside of boss showing void in bottom of threaded hole

3.4.2   Machinability Study

KCP's Process and Machining Evaluation Laboratory (PMEL) was tasked with determining if there was a difference between a wrought bar and the same alloy applied using the LENS process. The machinability testing techniques have been used on multiple ADAPT and CRADA studies at FM&T. End mill evaluations were based on a modified ISO 8688-2, Tool Life Testing in Milling, Part 2: End Milling. Drilling tests were based on procedures established for the USCAR CRADA and ADAPT project titled "Milling and Drilling Evaluations of Stainless Steel Powder Metallurgy Alloys.

Alloys evaluated in this study consisted of 304L Vacuum Arc Remelt (VAR), 316L, and PH 13-8 Mo stainless steel. Machining tests were conducted on purchased wrought materials. All specimens were machined on all sides and were square before initial tests. After the wrought machining tests were completed, the specimens were sent to Sandia National Laboratories at Albuquerque where the same alloy was applied by the

LENS method to the wrought specimen. Once returned to FM&T, the specimens were again squared up and the irregular top surface of the LENS layer was removed. The machining tests were then completed for the LENS material using the same conditions as for the wrought testing.

Testing revealed hardness differences between the wrought material and the LENS material of the same alloy for austenitic stainless steels. This difference will not make LENS modifications to the workpiece transparent to the machining process (i.e. LENS does not machine the same as wrought material). The increase in hardness in the austenitic LENS material is high enough to decrease tool life if the machining parameters are not adjusted. In the case of the precipitation hardened stainless steel the hardness of the LENS layer was similar to the wrought material, however testing on the PH 13-8 Mo stainless steel again showed that tool life was less in the LENS material.

It is important to note that while tool life decreased when machining the LENS material, the decrease was not so significant as to mandate different tooling or machining parameters. Using the same parameters as those set up for wrought material would yield slightly lower tool life, but not so much as to introduce significant additional cost to the manufacturing process.

The complete report including all machining data from the study can be found in Appendix E.

3.5 Investigation of the Mechanical Properties of LENS-Substrate Interface

For LENS to be used in part repair and modification applications, it is important to have confidence in the interface between the LENS material and the substrate, whether that be a machined part, a casting, or a previously deposited LENS part. To that end, a series of tests was conducted to study the interface between LENS and the substrate which included the following: fully LENS, LENS on LENS, and LENS on Substrate representing hybrid builds where the substrate becomes part of the final component. The fully LENS parts were used as a baseline and the other parts containing interfaces were compared to these baseline configurations. The study utilized both "thick" towers and "thin" walls to represent the two most significant heat conduction conditions experienced in LENS builds. A total of 13 different build scenarios were utilized in the testing and these are shown in Figure 3.5.A.
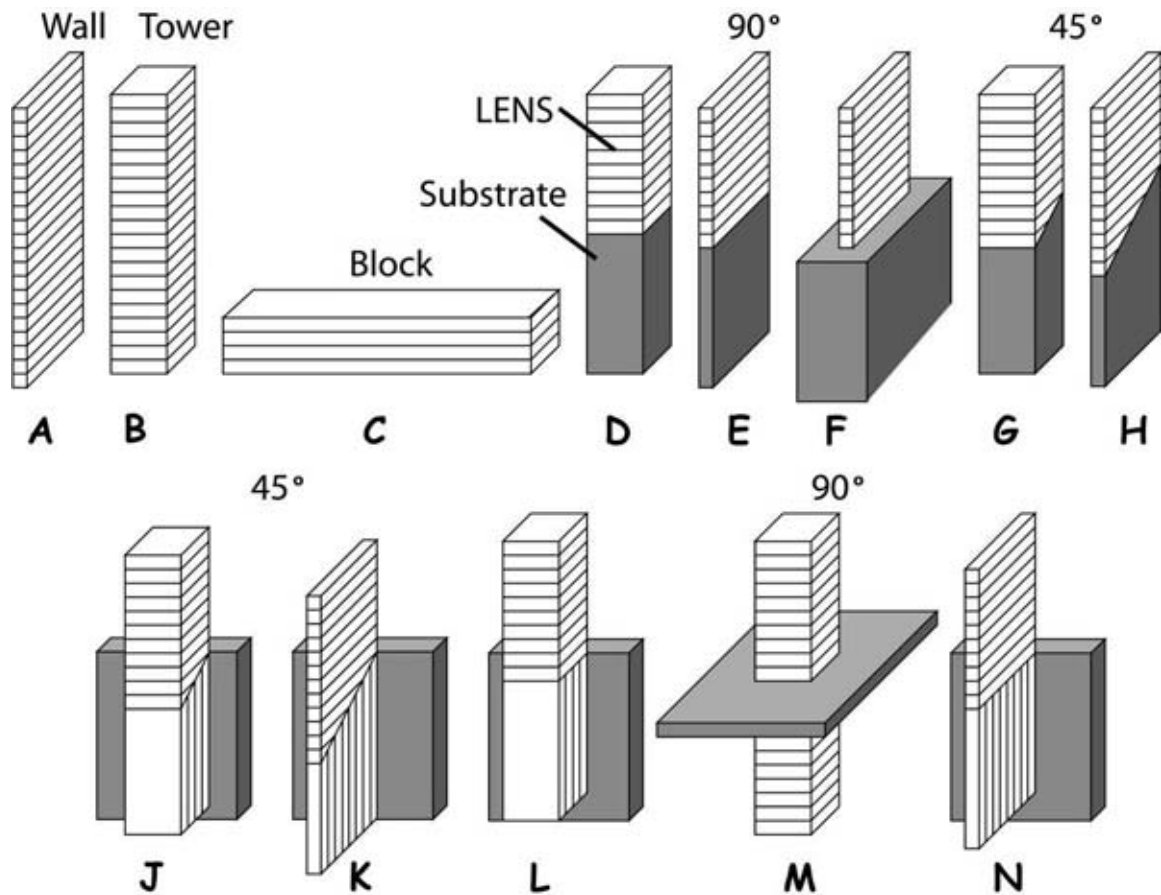
3.5.A: Schematic of 13 Different Types of LENS Deposited Tensile Test Specimens Representing Repair and Modification Geometries. The Stripes Represent the Build Layers and Show the Orientation in Which Each Section Was Built.

Two or three samples of each geometry were created and many of the samples are shown in Figure 3.5.B. The samples were then machined into tensile specimens. Round tensile bars with a 0.125 inch diameter and 0.5 in gage length were used for the Block/Tower deposited material and flat tensile samples 0.020 inches thick by 0.063 inch wide with a 0.5 inch gage length were used for the Thin Wall configuration. A knife-edge extensometer was used on the round samples, and a laser extensometer was used on the flat samples. The samples were strained using the standard 0.2 inches per minute cross head speed. The ultimate tensile strength, yield strength, and ductility as measured by both elongation and reduction in area were determined. For flat samples, both smooth and notched samples were evaluated. In order to assess interface characteristics, the notched samples were machined to bias the loading such that the fracture would initiate as close to the interface as possible. Strength values were determined by the usual analysis of the stress strain curves for both smooth and notched samples. However, values for notched samples are not representative of the actual strengths, and were only used for comparing relative strengths of the notched samples. Ductility as measured by reduction in area (RA) was expected to be similar for notched and un-notched samples to determine the precise effect of the interface. The quantity of data acquired by the testing was fairly large, so only an example is shown in Figure 3.5.C with the

remainder of the results being shown and discussed in Appendix I. In addition to the analytical measurements, the Appendix also contains qualitative analyses of the fracture surfaces and the microstructure of the parts tested.
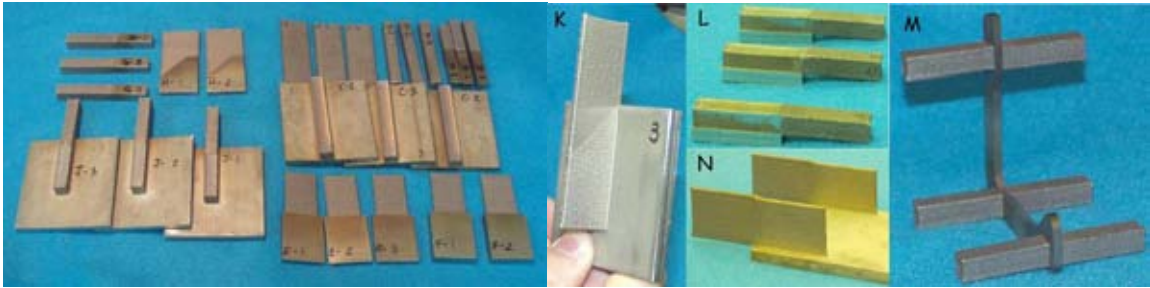
Figure 3.5.B: LENS Deposited Interface Samples Showing the Different Configurations Tested. Each Sample or Set of Samples is Labeled With Designations to Match the Previous Figure.
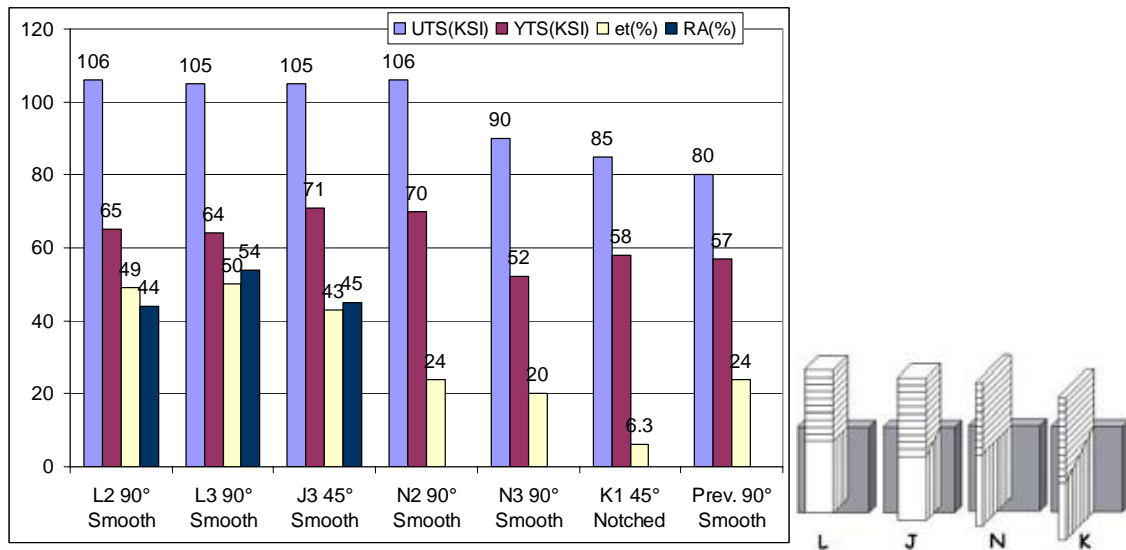
Figure 3.5.C: Results for LENS on LENS Tensile Tests Deposited with 90° and 45° Angled Interfaces

The tensile data for smooth tensile bars indicates good metallurgical bonding between LENS® deposits and the substrates for the range of configurations studied The yield strengths are substantially higher than a previous study of 304L stainless steel, and they are more like those reported for 316 stainless steel. This means that for both 316 and 304 stainless steels, it is possible to obtain LENS deposited material with about twice the strength as annealed wrought bar, but with no significant reduction in ductility, as is observed for the work hardened condition of wrought bar stock. Notched samples were also tested to force fracture at the interface between LENS deposit and substrate, and no differences in fracture mode from that of smooth tensile samples was observed. There were no significant differences in ductility from one sample to another or for duplicate samples, but there were some noticeable differences in fracture characteristics when examined in the SEM. Fracture, in all cases, is by ductile microvoid coalescence and based on matches of the periodicity of

46

the fracture feature and the periodicity of the interlayer interfaces, the differences appear to coincide with evidence of premature separation at inter-layer boundaries. In turn, these differences corresponded to documented abnormalities in the baseline deposition parameters. Samples not experiencing abnormalities in processing conditions did not exhibit this particular feature. By insuring that closed loop feedback control of the melt pool during deposition is engaged, the above mentioned types of abnormality are not expected to occur.

The microstructure was typical of previously characterized fully dense LENS deposits. The cross sections perpendicular to the deposition direction allow metallographic analysis of melt pool size and with interlayer and inter-pass overlaps. All samples exhibited adequate overlap to insure complete filling of void space, and complete melting and re-solidification of the feedstock. However, there were two irregularities: 1) The overlaps, although adequate, were not as uniform as possible, and 2) There was more noticeable isolated porosity and small oxide inclusions than previously seen in these materials. Again, by optimizing the closed loop feedback control system, features like this lack of uniformity can be overcome. The porosity did not appear to measurably degrade either the ductility or the strength. The oxide particles may originate in the powder feedstock. The fracture in all cases is by ductile microvoid coalescence, although some samples showed evidence of manufacturing defects traceable to abnormalities in process control. Future part fabrication monitoring and process control improvements are expected to eliminate and/or exclude parts with manufacturing imperfection from further consideration.

Based on these observations, it appears that the use of the LENS process to deposit 304L stainless steel onto wrought or previously LENS deposited material for component repairs and modifications does provide adequate interface properties and microstructure equal to or better than the base material. Although additional qualification, definition of acceptance criteria, and process control enhancements are needed prior to incorporation of the process into the suite of WR approved processes, the results of this work indicate that there are no apparent impediments to such qualification. Additional testing information is available in Appendix I.

3.6 Repair Process Qualification

The process qualification of LENS has been an important effort to assess the process control for LENS in creating components for high rigor applications. The broad topics of the process qualification are outlined here. The details of the qualification are reported in SNL document EER20063852SA.

3.6.1 Summary of the LENS Process Qualification

The Laser Engineered Net Shaping™ (LENS®) Technology Investment Project (LENS TIP) Team has the goal of creating a Process Quality Record (PQR) for the LENS process. The PQR generally requires three demonstrations: process control, process rigor, and process capability. Process control includes evaluations of the process controllability and repeatability especially with regard to their potential impact on part quality and performance. Process rigor requires that process procedures be established, formalized, followed, and monitored to assure part quality. Process capability is being shown through efforts to meet customer requirements for a NW part. The LENS team

chose the D-Bottle Bracket 1E0125 as a target application. Though this bracket is unlikely to be made with LENS for WR, the component design team offered for the LENS bracket to ride along in parallel subsystem testing to the conventionally machined bracket. However, to earn a place in this testing, it was necessary for the LENS bracket to meet certain requirements for dimensional geometry, mechanical properties, and dynamic response to weapons environments. Requirements were extracted from the environmental specification document, and adapted to the changing needs of the system and component engineers during their design phase. The team fabricated and tested LENS processed parts that were compared to conventionally-processed parts. The LENS parts met the specified performance requirements in time to be delivered to the W80-3 team, but subsystem level tests were not conducted due to cancellation of the LEP.

3.6.2   Process Report Activities

The process qualification report (PQR) requires that a process demonstrates control, procedural rigor, and capability when producing a component. In order to complete a PQR for the LENS TI project, the W80-3 D-Bottle Bracket 1E0125 was selected as a prototype LENS processed part for NWC applications. This part was chosen because it allowed a cost effective approach for investigation. Its size is small enough to allow making many parts, if necessary, at a reasonable cost to the project. The bracket also has fewer requirements leading to enhanced evaluation, lower risk to the customer, and lower costs for manufacturing and testing.

The first aspect of a PQR, process control, was demonstrated through repeatability tests showing that the process is capable of producing a statistically significant number of parts over an extended time period and achieving consistent results. The repeatability tests, measuring the mechanical properties and evaluating the microstructure of LENS-deposited material samples, have shown the ability to meet or exceed WR material specifications for 304L stainless steel as well. Process control requires that an analysis be performed to determine which process measurements are critical to the LENS manufacturing of the Reservoir Bracket or other high rigor components. Based on that evaluation, some instruments will require calibration and the team will demonstrate correct instrument usage including an understanding of the uncertainty inherent in the measurements. This is being verified by the quality engineer.

The second aspect of a PQR is procedural rigor; i.e., the process has defined procedures (work instructions) and the procedures are followed correctly by the operators. As part of procedural rigor, the drawings must be revision controlled as must software and other process documentation. A quality engineer is monitoring the activities of the LENS team as they produce the sample parts and will determine if the work instructions are followed, and that the work instructions adequately cover the activities required to deposit the brackets.

The third aspect of a PQR is the capability of the process. This is being demonstrated by creating bracket components and testing them to determine if they perform comparably to conventionally machined, wrought parts. The performance equivalency

was determined by comparing part mass, dimensional accuracy, mechanical properties, and dynamic response through modal and Haversine shock testing. This analysis determines whether the LENS-produced brackets would be eligible for inclusion in subsystem level, parallel path or "piggyback" qualification testing. Because the manufacturing method is selected many years in advance of subsystem testing (in this case 6-7 years), it is not feasible to request that LENS parts be used in primary path testing at this juncture. However, the system design group generously offered for the LENS subsystem to piggyback on unused sides of the shock table's tombstone so that data could be collected in parallel with the primary path, conventionally machined components. Some of the initial customer requirements that the LENS brackets must meet are the dimensional and geometric callouts of the part drawing AY1E0125. The LENS team developed a process to create near-net shape brackets that had sufficient material such that they could be machined to final dimension and inspected for compliance with drawing AY1E0125.

The other part requirements were determined by the DA. As with any NNSA system, qualification of components includes system, subsystem, and/or component level testing to specified environments (thermal, shock, vibration, normal environments, abnormal environments, nuclear safety, EMR, etc). In the case of the W80-3, the system level details are listed in the ES1E0003 environmental specification. For the D-Bottle Bracket, all requirements except EMR, abnormal, and nuclear safety requirements were applicable. The requirements for the brackets were obtained from the system level to start, and later from the subsystem and component levels.

Because this bracket is an integral part to the GTS subsystem, both GTS subsystem and W80-3 System level testing was planned. The GTS plan was to include a very rigorous large scale (i.e., expensive) qualification program to demonstrate to the W80-3 System that the GTS subsystem met the ES1E0003 requirements. Because of the expense of the full subsystem test, LENS brackets were required to demonstrate quality and performance equivalent to conventionally machined wrought 304L parts. The requirements for the LENS TI team were to demonstrate equivalency before the PRT would allow LENS parts to be used in their expensive subsystem tests.

The equivalency testing chosen by the DA required that LENS brackets meet the same preliminary or "screening" GTS sub-assembly test as the conventionally-machined, wrought 304L brackets. This defined the requirements for the LENS team for qualification of a LENS fabricated D-Bottle Bracket. The team's challenge was to manufacture parts that met the criteria for system level testing, before the W80-3 subsystem tests were carried out. Parts were manufactured using in-house LENS capabilities at SNL, which are equipped with necessary attachments and quality personnel to monitor process consistency. The net-shape parts were finish machined and inspected using calibrated instruments. Measurements of part dimensions were made before and after testing, and the data was recorded. There were two primary requirements regarding the dynamic response of the LENS parts that had to be met before a LENS part could be utilized in the subsystem level tests: a mechanical tuned

block response (or "ping") test; and a mechanical environment block drop test (or "Haversine shock test".)

The "tuned" block sub-assembly included the bracket and a few other GTS components mounted to it. The block was tuned to provide a similar mechanical response via a ping test (basically the block was tuned to match the first 2-3 fundamental frequencies as the W80-3 did when pinged with a rubber hammer.) Tests were conducted with both LENS-processed parts and machined wrought parts and the test results compared. The results indicated very minor differences in the results between types of processing.

The second dynamic response test for the brackets was a mechanical environment block sub-assembly drop test. The brackets were measured at critical locations before and after the testing to quantify any geometric changes induced by the test. For the mechanical environment block sub-assembly drop test, the brackets were mounted to a plate and a few other GTS components mounted to the bracket. This sub-assembly was then mounted to a cross arm on the test rig and the lifted to the correct height. A material was placed under the cross arm to induce the correct duration of the impact and the test rig was dropped. Sensors on the rig measured the dynamic response of the subsystem. In selecting the parameters of the test, the most demanding mechanical environments listed in the ES were used. This testing demonstrated the response of the system as well as the strength of the bracket to assure that inclusion of LENS brackets in parallel subsystem testing would not jeopardize the stockpile directed components (conventionally machined).

The LENS parts performed well in the testing, meeting the DA's requirements, and were deemed by the DA component designers to have successfully met the requirements clearing the path for the LENS brackets to be included in parallel path subsystem testing. By meeting these requirements, the LENS TIP team achieved the goal of manufacturing and testing LENS deposited brackets in time for inclusion in the scheduled W80-3 GTS subsystem qualification testing. Unfortunately, this testing did not occur due to the cancellation of the LEP.

4 APPLICATIONS PERFORMANCE DATA

4.1 Reclamation Welds and Gas Bottles

4.1.1 Performance Data

Burst Testing Reclamation Weld Test Bases
The reclamation test samples and bottles were burst tested using hydroburst testing equipment. The samples were connected to the high pressure fittings and pressurized to failure in about one minute. The burst tests were videotaped so the burst location could be observed.

All of the reclamation test welds failed in the fill stem tube wall at pressures between approximately 58 to 62 ksi, which is consistent with the expected material properties of these stems. A graph of the data is shown in Figure 4.1.1A.

LENS Repaired Reclamation Base Burst Test
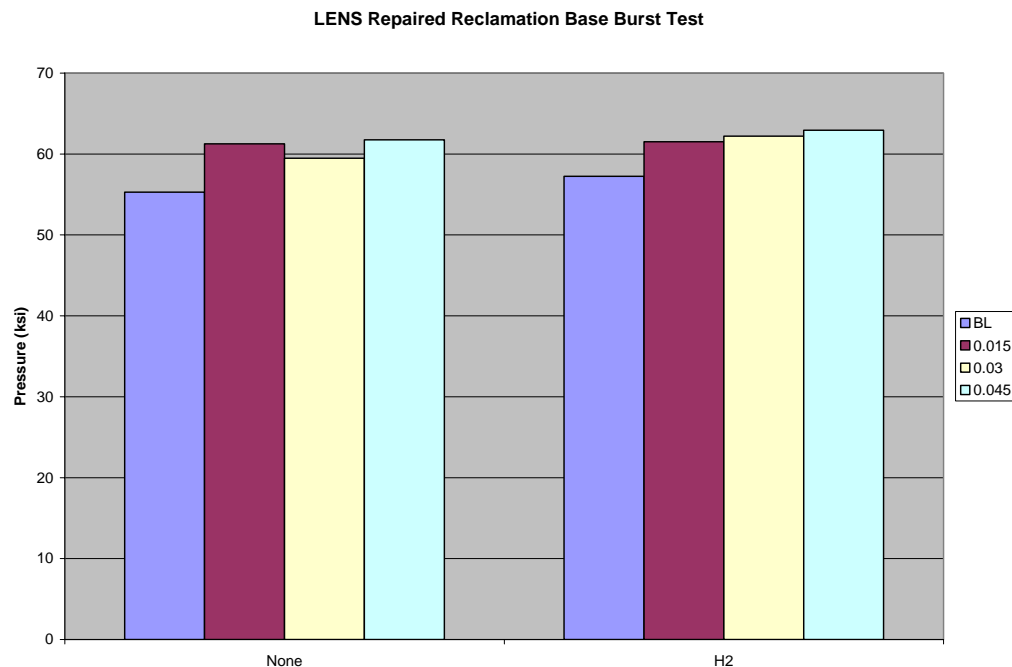
Figure 4.1.1A: Hydroburst Pressures for Baseline, LENS® Repaired and Hydrogen Charged Fill Stems Show That no Adverse Effects are Indicated.

Burst Test Gas Sampling Bottles
The sample bottles were sealed on one end with a threaded plug and fitted with a high pressure fitting on the other end for pressurization. These samples were also hydroburst tested to failure using a pressurization time of approximately 1 minute. The vessels all exhibited a longitudinal tear that apparently initiated near the center of the vessel, at the location of the highest elastic strain. The data for the as-received sample bottle is comparable to the vendor certification data for these vessels. The as-notched

samples in the uncharged condition exhibited a reduction in both burst pressure and failure ductility. LENS® repair for a 0.010 inch deep notch is able restore the burst pressure, however, the uniform strain (ductility) is not fully restored, Figure 4.1.1B

Non-Hydrogen Charged Gas Sample Bottles
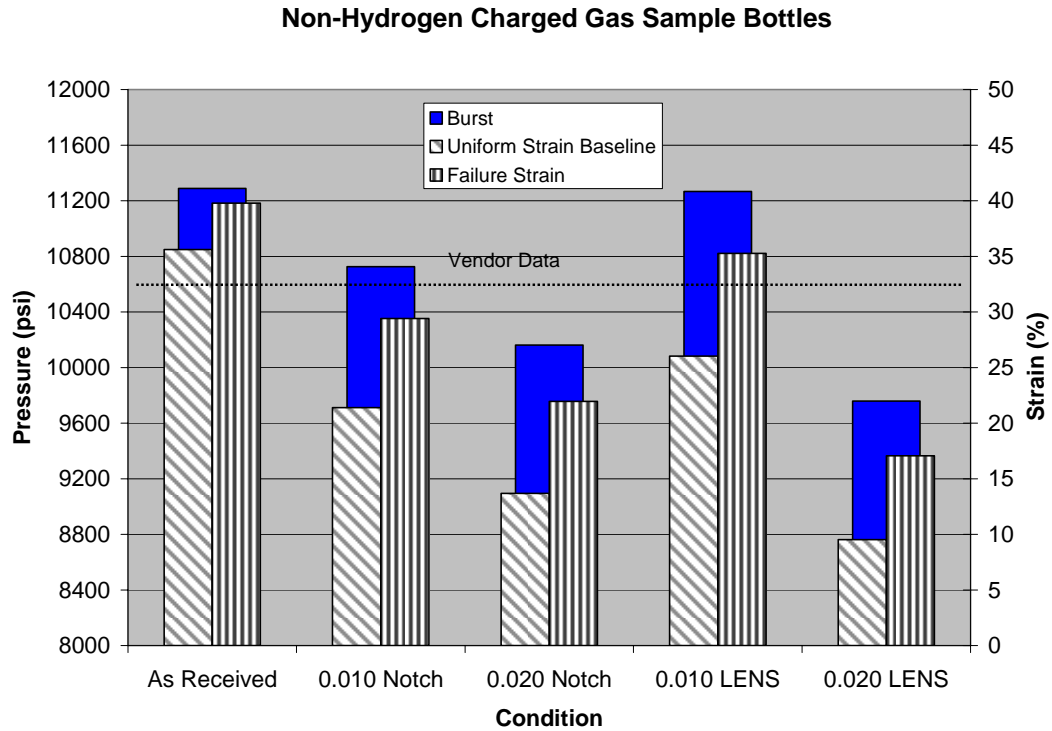
Figure 4.1.1B: Effect of Notches and LENS® Repair on Burst Properties of Gas Sample Bottles

The hydrogen charged samples exhibit interesting results. The baseline data shown in Figure 4.1.1B is repeated in Figure 4.1.1C along with the hydrogen sample data. The hydrogen charged samples show some strengthening due to hydrogen charging. This phenomenon has been seen in previous tensile test work. The hydrogen data plotted in Figure 4.1.1C is the average of the two points for each condition. As was the case for the baseline samples, the presence of notches reduced the burst pressure for hydrogen charged samples, although the fractional reduction in burst pressure was less for the hydrogen charged samples than the baseline. The burst ductility is lower for the hydrogen charged samples with notches.

Burst Test Results
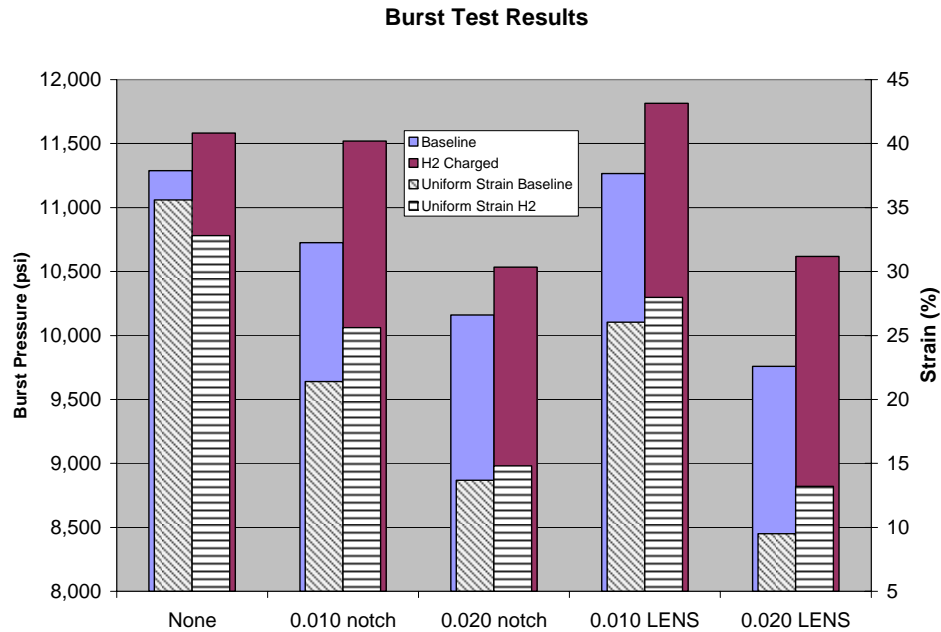
Figure 4.1.1C: Effect of Hydrogen on Baseline and LENS® Repaired Samples

The sample with the 0.010 inch notch that was LENS® repaired actually demonstrated a slight increase in strength over the baseline condition for hydrogen charging and essentially no loss for the baseline. Both the 0.020 inch notched and 0.020 inch notch and LENS® repaired sample exhibit burst pressures and uniform strains that are similar in value.

The appearance of the burst tested gas sample bottles exhibited the expected failure with the bottle opening up axially. In addition, all of the samples with notches failed in the notch. There was one exception for the LENS® repaired samples and Sample 0.010 LENS® repaired 1 failed in vessel body away from the LENS® repair.

The fracture surfaces of the LENS® repaired surfaces were also examined. The LENS® material appears to have cracked axially and some of the samples exhibit a possible delamination. This failure mode may be indicative of the deposition method and deposition direction.

4.1.2 Repair Process Parameters

The LENS processing of the reclamation welds required different processing parameters than those used for the gas bottles due to the differences in geometry. The reclamation weld samples were filled using a 4th axis mounted in the machine to allow the laser to access both the bottom of the bore and the wall of the bore. The setup is shown in Figure 4.1.2.A (left). The weld base rotated under the laser beam while the laser progressed from the wall to the center of the bore effectively reducing the depth of the bore. The laser then reset to the wall of the bore and deposited another layer on top of the first one. This method produced good adhesion of the LENS material with the

outside wall which was most important to the bore. As the laser approached the center of the bore, the heat increased greatly causing a knob to build in the middle of the bore. This material was not good quality, but it was not important since the application was primarily concerned with the diameter of the bore. The problem is shown if Figure 4.1.2.A (right).
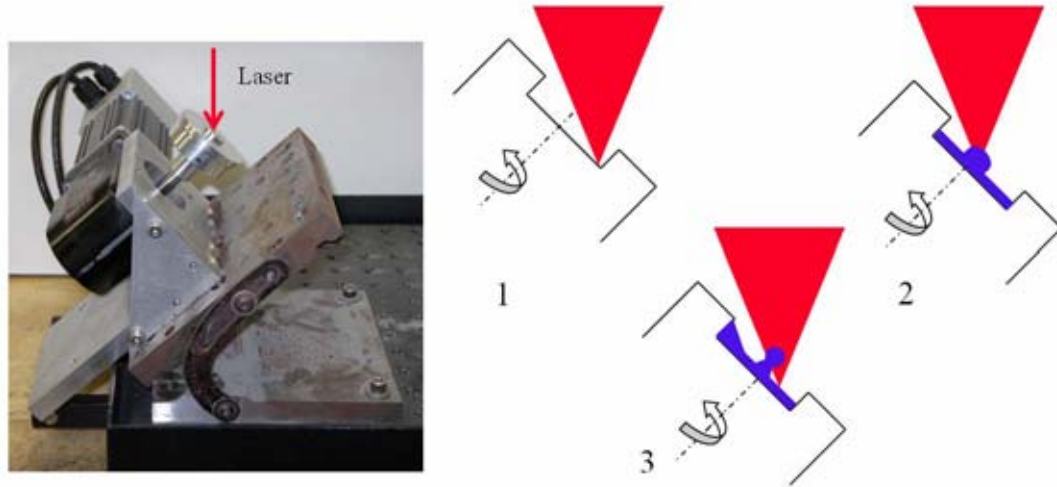
Figure 4.1.2A: The Reclamation Weld Base Overbores Were Filled Using a 4th Axis Mounted in the LENS Machine (Left). The Procedure Involved Filling the Bore Layer by Layer Which Resulted in a Boss Being Created in the Center of the Bore (Right)

The sample bottle surface flaws were repaired by mounting the bottles in the machine with the flaw oriented parallel to one of the machine axes. The bottle was positioned in a v-block and butted against a locating pin to repeatably position the bottles. The flaw was then filled with 2 layers for the 0.010" deep flaws and 3 layers for the 0.020" deep flaws. This method produced excess material which could be machined to final dimension for testing. The process parameters can be found in Table 4.1.2.A. Additional discussion of the repairs is found in Appendix H.
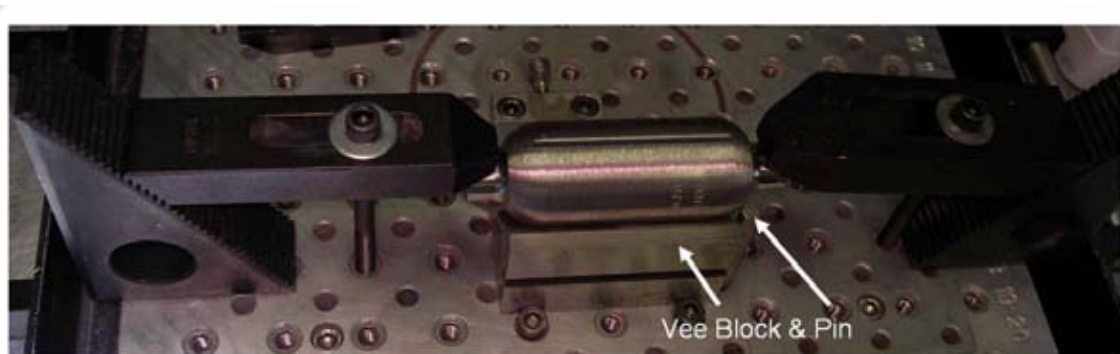
Figure 4.1.2.B: Fixturing for Surface Flaw Repair of the Gas Sample Bottles

Table 4.1.2.A: Process Parameters Used for the Repair of Reclamation Base Bores and Gas Sample Bottle Surface Flaws

	Reclamation Base Bore	Sample Bottle Surface Flaw
Powder Flowrate(gpm)	23	37
Laser Power (W)	535 W (29A)	-
Filter %	70%	70%
WP Intensity	-	300
Fill Area (pix)	-	750
Border Area (pix)	-	750
Axis Feedrate (ipm)	22+ (fast center)	22
Material	Virgin 304L	Virgin 304L

4.2 W87 Firing Set Housing

4.2.1 Performance Data

In an attempt to qualify the use of LENS for WR repairs, the W87 Firing Set Housing (see Figure 4.2.1 below) was selected as the Kansas City Plant's test component. Three housings that had been previously scrapped were obtained for the study. Specific part features were removed from each of the housings and rebuilt by Sandia National Laboratories by applying PH 13-8 Mo stainless steel material using their Optomec LENS machine. The parts were returned to the Kansas City Plant and put through a rigorous evaluation.

Figure 4.2.1: View of three W87 Firing Set Housings repaired with LENS

This evaluation of the firing set housing repair has revealed many positive reasons for using LENS as a qualified procedure for WR component repair. First, an optimized repair process will not discolor the component receiving the repair nor will it distort the part due to heat input. The LENS material deposited exhibits good hardness properties and is heat treatable if necessary. The material is readily machinable, but care should be taken to ensure there is enough overbuild to achieve 100% cleanup on all repaired surfaces. After machining, dye penetrant inspection will reveal any surface cracks and indicate the extent to which those cracks penetrate the part. X-ray inspection was proven effective in detecting sub-surface voids. Testing to determine if the LENS material is hermetic was not performed, but is recommended to be done on potential WR applications.

The LENS repair of W87 Firing Set Housing was mostly successful, with only a couple of issues. Both of the issues could be resolved with further process development for the firing set housing. The issues for this repair attempt were the inability to fill countersunk holes to effectively repair machined threads, and the presence of in-line porosity that arose from the linear deposition technique used in the buildup of the can lip. More process development in filling small diameter holes needs to be performed to get this technique perfected, and the linear deposition method for depositing material on thin walls also needs to be altered (i.e. add a pass where the two LENS passes overlap) for this particular repair.

The microstructure of the LENS/housing interface as well as a laser weld joint between the LENS material and a 304L stainless steel plate looked typical of laser weld joints. The grains of the LENS/housing interface and the laser weld area were of typical size and structure, and exhibited no detrimental secondary or tertiary phase formations.

With the addition of a rotary table and trunion, true five-axis capabilities are now available on the Sandia Optomec LENS machine, making any accessible surface a candidate for repair or build up with the LENS process. Each particular part repair or build will require some process development before being deployed for WR use. It is recommended that LENS be used to build complex geometries which would normally require expensive castings or to repair product that is very expensive to scrap. The cost of the LENS build/repair coupled with the inspection techniques required to ensure the quality of the added features does not lend itself for use on low value items.

The entire report on the repair of the W87 Firing Set Housing using LENS can be found in Appendix D.

4.2.2   Repair Process Parameters

The LENS repair of the W87 Firing Set Housing required deposition on three features. These features were the cover weld flange, the can 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 cover weld flange is a curved feature as shown in Figure 4.2.2.A. 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. 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. The LENS team attempted build up the face in this location, but was somewhat unsuccessful due to the angle of the incoming laser, which is a difficulty that would no longer be an issue. Overall, however, the flange was satisfactorily repaired. The process values are given in Table 4.2.2.A and more detailed discussion is given in Appendix H.
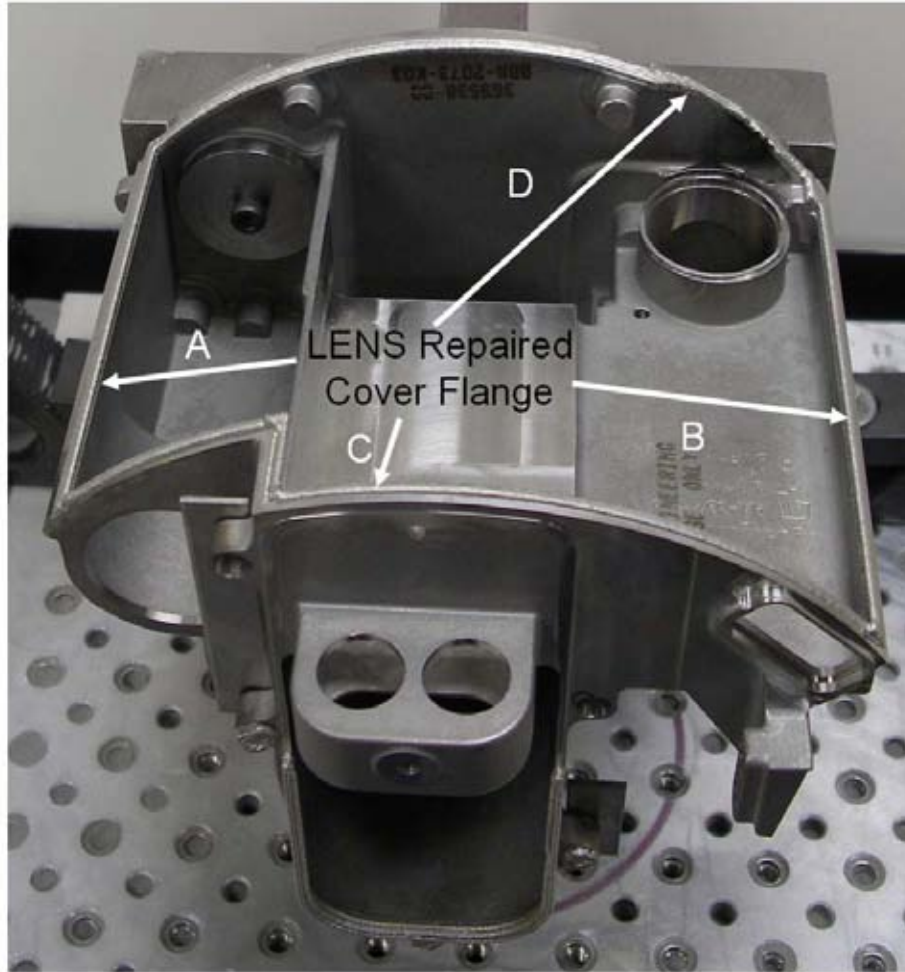
Figure 4.2.2.A: LENS Repaired Cover Flange Showing Straight Sections (A, B), Curved Sections (C), and Compound Curved Sections (D)

The can lip was repaired by placing two side-by-side LENS passes around the periphery of the can as shown in Figure 4.2.2.B. Because of the axis limitations of the LENS machine at the time of the repair, a tall feature at one end of the lip 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. Additional notes regarding the can lip repair are in Appendix H and the processing conditions are in Table 4.2.2.A.
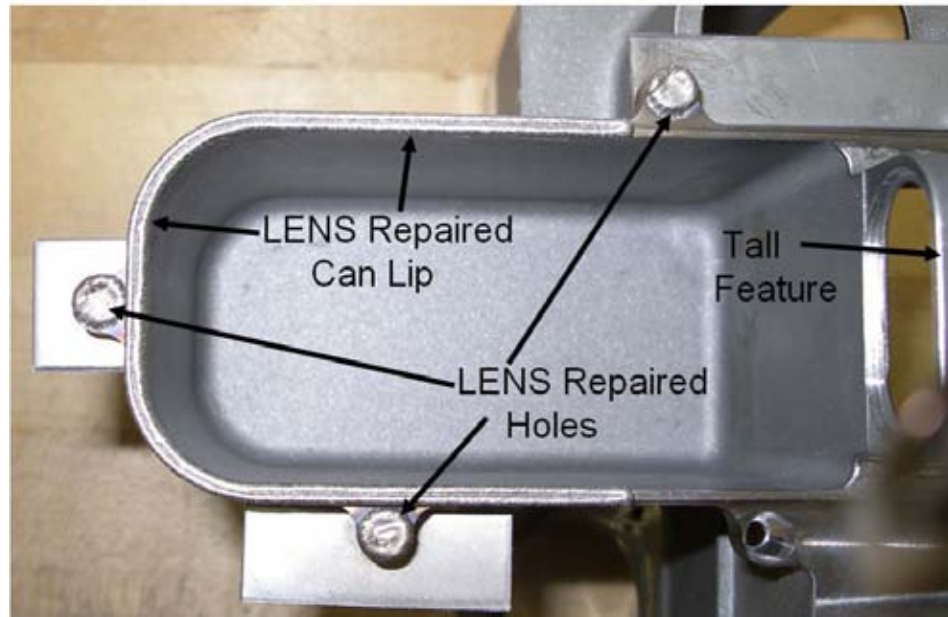
Figure 4.2.2.B: The LENS Repaired Can Lip and Holes. Note that the Tall Feature on the Right Side of the Figure Prevented the Entire Can Lip From Being Repaired

The final 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 that left a steeply angled side 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. A discussion of the hole filling is presented in section 2.4 with some of the lessons-learned shown in Figure 2.4.A. 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 in general. The process is covered more thoroughly in Appendix H and the process parameters are given in Table 4.2.2.A

Table 4.2.2.A: LENS Process Parameters for W87 Can Lip and Weld Flange Repair and Hole Filling

	W87 Can Lip & Weld Flange	W87 Holes
Powder Flowrate (gpm)	24	21
Laser Power (W)	245 W (24A)	190W (23A)
Filter %	140%	140%
Axis Feedrate (ipm)	18	18
Material	Virgin 13-8	Virgin 13-8

4.3 W80-3 D-Bottle Brackets

The W80-3 D-Bottle Bracket was chosen as the part to be used in the qualification of LENS. The parts were to be built by the LENS process, finish machined, and then used in several weapons environment tests. The results of these tests would be compared to tests of conventionally machined components, and if results were sufficiently similar, the LENS parts would then be used in parallel subsystem-level shake table testing with the conventionally machined parts. This would allow an equivalency analysis of the LENS parts with the parts destined for inclusion in the weapons system. The proof tests that the brackets had to pass for subsystem testing inclusion were mass, modal analysis or ping test, and a drop test.

4.3.1 Performance Data

For the testing, a set of 3 LENS deposited and finish machined brackets were directly compared with a set of 3 conventionally produced (CP) brackets. The brackets were compared on the basis of mass, modal analysis, and a drop test. In the mass analysis, the LENS parts were 3% heavier and had a slightly greater variability in weight than the CP parts. However, this small difference was deemed to be close enough so long as there were no problems identified in the ping and drop tests. The increased weight of the LENS parts shows that there was no significant porosity in the parts.

In the ping test, the parts were suspended in a free-free state and an instrumented hammer was used to determine the free-state modal frequencies. Figure 4.3.1.A shows the 1st, 2nd, and 3rd modes for the CP and LENS brackets. Not surprisingly, the natural frequency and harmonics were slightly lower for the LENS parts due to the higher mass. In repeatability, the CP parts were all within 1% of each other while the LENS parts were within 2% of each other. The LENS parts were within 5% of the CP parts and both sets exhibited similar structural dynamic behavior and were deemed to be quite acceptable.
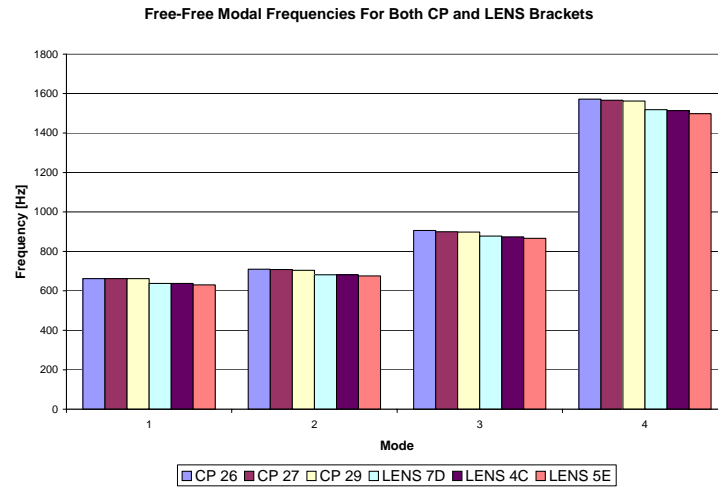
Figure 4.3.1.A: Free-Free Modal Comparison of LENS and Conventionally Processed (CP) Brackets Showing Very Similar Dynamic Behavior and Good Repeatability

The LENS and CP brackets were also used in modal testing of the subsystem assembly. In this test, the brackets were bolted into the assembly and again excited with an instrumented hammer. The parts were assembled and disassembled multiple times to ascertain if there were any differences with repeated assembly and none were found. These tests exhibited greater scatter than the free-free tests due to the differences in contact stiffness between the brackets. As seen in Figure 4.3.1.B, the CP parts had less than 8% variability, the LENS parts had less than 5% variability, and all parts together had less than 16% variability. Interestingly, the LENS parts had less variability in contact stiffness than the CP parts, though this is likely to have as much to do with the finish machining as the source of the material.

Modal Frequencies For Both CP and LENS Brackets in Assembled Configuration
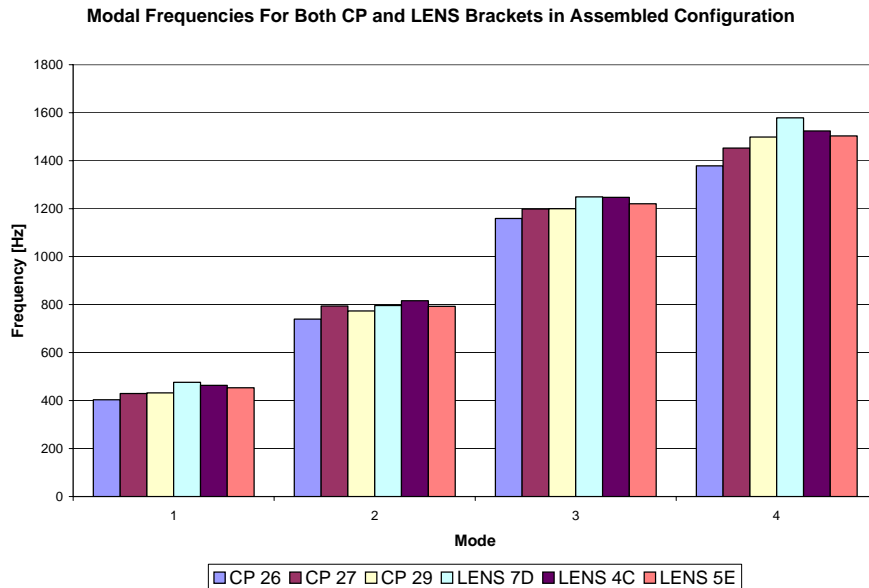
Figure 4.3.1.B: Modal Comparison of Subsystem Assembly Containing Conventionally Processed (CP) and LENS Brackets

The subsystem assemblies containing LENS and CP parts were then subjected to Haversine Shock drop tests. In these tests, a sled attached to the subsystem assembly was dropped a prescribed distance onto a tuned surface to achieve the desired Haversine Shock input.   In these tests, the response of the LENS parts was virtually indistinguishable from the response of the CP parts in axial and cross-axial directions. The peak on-axis accelerations were all within 2% of one another.

Based on these tests, the design agency determined that the LENS parts could be used in parallel path testing of the subsystem. Unfortunately, cancellation of the system program prevented this test from occurring. Additional information about the bracket preparation and testing is given in Appendix F.

4.3.2   Repair Process Parameters

The LENS processing of D-Bottle Brackets brought light to a wealth of new knowledge involving the utilization of LENS deposited parts for high rigor applications. The first attempts at depositing the bracket were targeted at utilization of a wrought plate structure that would become part of the bracket. In this scheme, the bracket features would be deposited onto the plate structure which would minimize the time required to deposit and finish machine the parts. Attempts to create this type of bracket were ultimately unsuccessful due to heat distortion of the thin plates.

The next approach was to build the full brackets with LENS material. This approach required that the bracket model be modified to include a support structure as well as an offset of the part surfaces to leave sufficient material for the machining processes to clean up fully. Parts were completed in this manner (shown in Figure 4.3.2.A) and machined to final tolerance. During this process, it was determined that several process improvements would be necessary to make the process more efficient and to increase

yield. First, the part had been LENS deposited with the holes in tact with offset surfaces. The rough holes made it more difficult for finish machining because the existing hole would guide a drill bit to a location that might not be the right location if the part was not located in the machining process exactly as it had been in the LENS process. This forced KCP to machine the bracket holes by helically interpolating an end mill into what was a somewhat deep hole for the allowable end mill diameter. This was expensive, slow, and could potentially add error to the machining process. Secondly, the part was deposited on available substrates which were flame cut 0.75" stainless steel and mounted flat on the surface of the platen of the LENS machine. This inexact fixturing caused great difficulty in locating the rough part in the machining process. The substrate edges were not square and the substrate had distorted with the cooling LENS build and was no longer flat. In machining, it was difficult to determine what was flat and how to locate the part. The result was that some parts did not clean up in the machining as is shown in Figure 4.3.2.A. There was, however, some very good news. Partway through the process, the bracket was redesigned to include the tab shown at the far left of Figure 4.3.2.A. This tab had not been in the original LENS build, but was easily added to the parts using LENS. This part modification was exactly the goal of the project and clearly demonstrated the utility of LENS for repair and modification.

**Figure 4.3.2.A: LENS Deposited Brackets in Near Net Shape and Finish
Machined Showing Some of the Lessons Learned**

Armed with the new knowledge gained in the previous round of processing, a new set of brackets was deposited and machined as shown in Figure 4.3.2.B. These brackets utilized a new fixturing system in which a machined substrate was positioned and doweled on a perforated subplate. The part could thus be located in both the LENS machine and in the machining process in a repeatable manner. Additionally, the substrate plate was positioned on 3 button locating pins so that even with deflection of the substrate plate, the part would be located on the exact same 3 points. The parts were deposited with additional wall offset thickness to guarantee cleanup, and the holes were all filled in so that the machining process could position the holes precisely in relation to the other machined features using a drill, a fast and economical process.
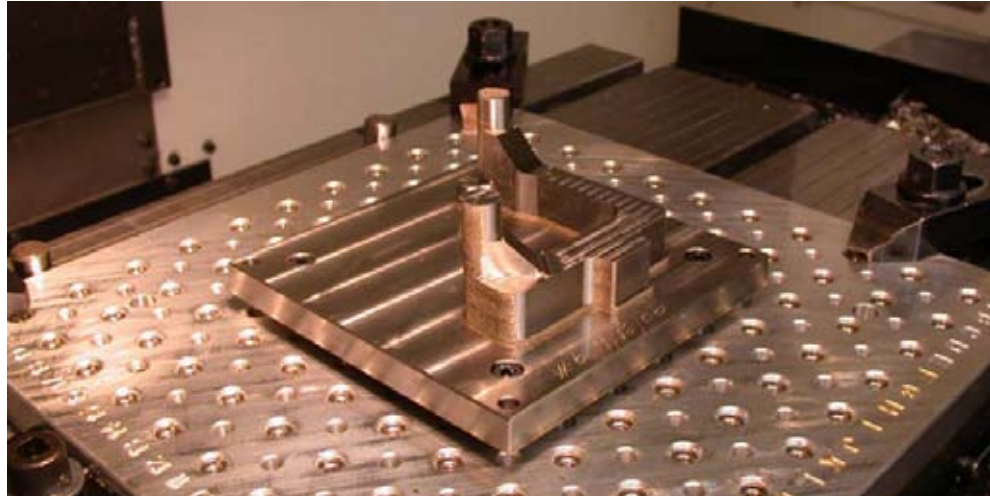
Figure 4.3.2.B: LENS Deposited Part During the Machining Process. The Fixture Plate and Machined Substrate Were Used in the LENS Machine As Well To Match Locating Positions. Note the Lack of Any Holes in the LENS Deposited Part.

The brackets are a large part to deposit and the process parameters were relatively easy to determine because of the very uniform heat conduction pathways through the part. The processing conditions are given in Table 4.3.2.A and more information regarding the LENS development process and the finish machining is presented in Appendix F.

Table 4.3.2.A: LENS Processing Parameters for Reservoir Brackets

	Reservoir Bracket
Powder Flowrate (gpm)	44
Laser Power (W)	480-575 (28-30A)
Filter %	80%
WP Intensity	300
Fill Area (pix)	750
Border Area (pix)	750
Axis Feedrate (ipm)	19.8
Material	Virgin 304L

4.4 Y-12 Test Rings

4.4.1   Performance Data

Y-12 test rings were supplied to Sandia National Lab to determine whether the LENS process could deposit material on a relatively thin wall ($1/8^{th}$ inch) section without any appreciable amount of distortion or porosity. After LENS processing, the rings would be machined with a step joint on the end of either the inner or outer diameter so the two could fit together. It is important to note that the pipe sections supplied by Y-12 were not very round.

Although the out-of-round sections made it more deposition more difficult, the LENS material was successfully deposited on the pipe sections. The pipes sections were measured before and after processing to determine the dimensional stability. The average change in diameter of 10 different sections was 0.02138 inches. A significant amount of change can be contributed to the pipe sections out-of-roundness and splatter that solidified from the LENS deposition. Given these two factors, the dimensional stability is satisfactory. After machining, some of the pipe sections were also sectioned and observed macroscopically, as seen in figure 4.4.1.A below, and microscopically for any porosity. No porosity could be found at the transition zone or the bulk of the LENS material in the pipe sections.

The entire report on the repair of the Y-12 Test rings using LENS can be found in Appendix G.
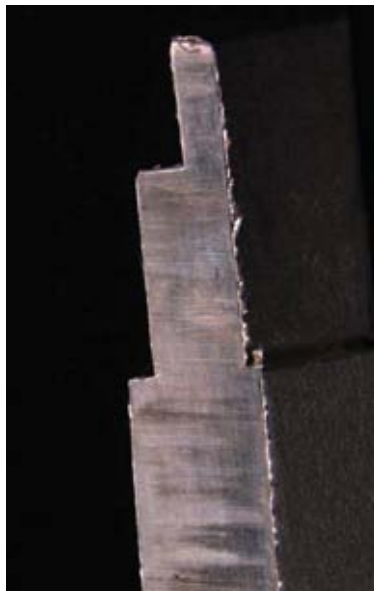

Figure 4.4.1.A: LENS Repaired Step Joint Ring Showing No Porosity.

4.4.2   Repair Process Parameters

The LENS processing for the step joint rings required that material be added to the end of each ring section so that the material could be machined into step joint halves and the halves fitted together. The ring sections, shown in Figure 4.4.2.A were welded seam 304L pipe of about 4inch diameter with $1/8^{th}$ inch wall thickness. The rings were fixtured in the LENS machine with the axis of the cylinder parallel to the Z axis. Rings of LENS material were then deposited on the top of the pipe sections. There was some difficulty in depositing the LENS material as some of the rings were not very round. This out-of-round condition led to sections of the pipe where the LENS material spattered down the side of the ring. One of the goals of the evaluation was to measure the pipe sections before and after LENS deposition to determine what dimensional change had taken place. The spattered material made the data harder to analyze. However, the LENS material was successfully applied to the top of the ring sections and the step joints, machined into the LENS material, fit together quite well.
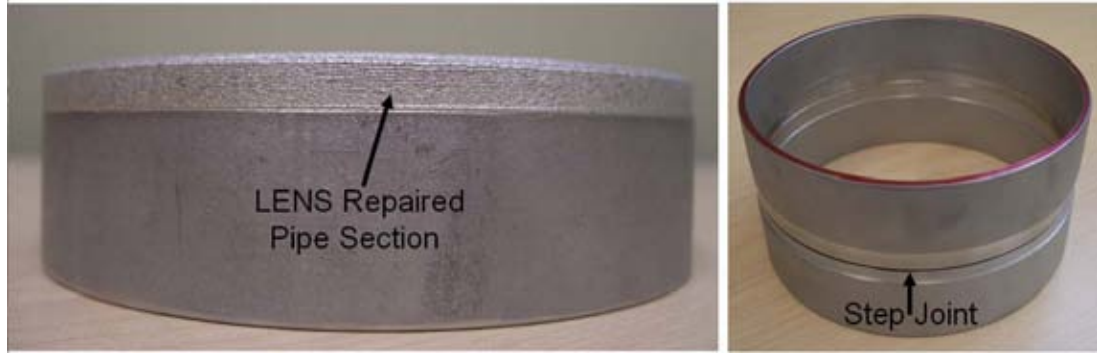
Figure 4.4.2.A: LENS Repaired Step Joint Rings Showing the Net Shape Repaired Section (Left) and the Machined Step Joints on 2 Rings Assembled (Right)

The LENS process used a conformal approach in which concentric rings of LENS material were deposited for the ring width on each layer. The Z axis was then stepped up by the layer thickness and the process was repeated. There were no problems with variable heat conditions around the build and the rings were thick enough that heat dissipated quite well. The process parameters used are given in Table 4.4.2.A and additional processing information is given in Appendix H.

Table 4.4.2.A: LENS Process Parameters for Step Joint Ring Pipe Sections

	Step Joint Rings
Powder Flowrate(gpm)	38 (475rpm)
Laser Power (W)	535 W (29A)
Filter %	70%
WP Intensity	400
Fill Area (pix)	750
Border Area (pix)	750
Axis Feedrate (ipm)	22
Material	Virgin 304L

5 CONCLUSION

The purpose of the *Qualification of LENS for the Repair and Modification of NWC Metal Components* project was to investigate the applicability of the Laser Engineered Net Shaping™ (LENS®) process for repairing or modifying high rigor metal components. The project included investigation into basic material properties, repair techniques, weldability, machinability, heat treatment, corrosion resistance, hydrogen compatibility, and interface characteristics. These criteria were studied initially on material analysis samples and later on real or mock-up weapons components that were repaired or made as fully LENS parts. Each site supplied components with sample repair or modification needs for a broad range of applications including weld flange replacement, bolt hole filling, overbore filling, surface flaw repair, step joint replacement, and fully LENS bracket fabrication. The LENS repairs/modifications were selected to demonstrate the capability on a wide range of components that included W87 firing set housings, reclamation weld bases, sample gas bottles, step joint rings, and W80-3 D-bottle brackets. In addition to the above applications, the LENS deposited D-bottle brackets were subjected to weapon environment testing for structural dynamics and shock.

The studies showed LENS material to have superior strength to annealed material while still maintaining sufficient ductility to meet the requirements for 304L, 316L, and PH 13-8 Mo stainless steels. The LENS materials and LENS-substrate interface materials showed corrosion resistance similar to the parent material, hydrogen compatibility with no significant increase in hydrogen embrittlement, machinability similar to the parent material with only a slightly higher tool wear rate to match the increased strength of the material, and heat treat characteristics similar to that of the parent material. The repair scenarios showed that most of the repairs would have benefited from additional process development for the repair, something that wasn't possible due to the very limited number of samples and the highly compressed timeline of the project. The weapon environment testing showed the equivalency of the LENS deposited brackets to the conventionally produced brackets causing the design agency to approve the brackets for parallel-path, subsystem-level testing in weapon environments. From these results, the LENS process was qualified and the increased procedural rigor necessary for qualification was implemented. The testing showed LENS to be an excellent alternative to scrapping components that were machined incorrectly, undergoing design revision, or in need of repair because of weld removal. This is especially true when the component has high value due to substantial machining or significant casting cost. Overall, LENS repaired components have been shown to meet the requirements for many high rigor applications while giving product and process engineers a new tool for repairing or modifying metal part geometry with confidence.

6 REFERENCES

The following references are process documentation that is held at Sandia National Laboratories. The documents describe basic machine usage, safety, and environmental aspects of the process.

- WI_1E0125_001 "LENS Deposit of D-Reservoir Bracket 1E0125" – work instructions including part prep and fixturing
- OP-2400-2006-003 "LENS General Operating Procedure" – includes machine startup, shutdown, emergency shutdown, atmosphere control, laser, maintenance, powder feeders, process gas, WPAC system
- PHS 976551697-012 – Includes general process safety
- eTWD010117001 Rev 0 – Discusses safe machine maintenance
- eTWD 020115001 Rev 2 – Discusses laser alignment, operation of machine interlocks, safe metal powder handling, and electrical troubleshooting

7 APPENDICES/TASK REPORTS

The documents listed in the Appendices are included with the electronic copy of this document. Each report was prepared by the participating sites and contains a more complete report of the evaluations completed at that site. Each of these reports has gone through the review and approval / release process at the site that created the document and the distribution was determined by the site.

APPENDIX A: PERFORMANCE OF LASER ENGINEERED NET SHAPE™ (LENS®) MATERIALS AND COMPONENTS IN HYDROGEN (U) – WSRC-STI-2006-00095 REV. 0

APPENDIX B: CORROSION PROPERTIES OF LENS 304L AND 316L STAINLESS STEELS (U) Y/DV-2002

APPENDIX C: STRESS RELIEF OF 304L STAINLESS STEEL LENS MATERIAL (U) KCP-613-8193

APPENDIX D: LENS REPAIR OF W87 FIRING SET HOUSING (U) KCP-613-8194

APPENDIX E: COMPARISON OF MACHINING PROPERTIES OF LENS APPLIED LAYERS TO THE SAME WROUGHT ALLOY (U) KCP-613-8035 MOD

APPENDIX F: PROCESS QUALIFICATION AND TESTING OF LEN® DEPOSITED AY1E0125 D-BOTTLE BRACKETS – SAND2006-6431

APPENDIX G: LENS REPAIR OF Y-12 TEST RINGS (U)
Y/DV-2003

APPENDIX H: LASER ENGINEERED NET SHAPING™ (LENS®) FOR THE REPAIR AND MODIFICATION OF NWC METAL COMPONENTS – SAND2006-6551

APPENDIX I: ON THE INTERFACE BETWEEN LENS® DEPOSITED STAINLESS STEEL 304L REPAIR GEOMETRY AND CAST OR MACHINED COMPONENTS – SAND2004-4035

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