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On the Interface Between LENS® Deposited Stainless Steel 304L Repair Geometry and Cast or Machined Components

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Abstract

Laser Engineered Net Shaping™ (LENS®) is being evaluated for use as a metal component repair/modification process for the NWC. An aspect of the evaluation is to better understand the characteristics of the interface between LENS deposited material and the substrate on which it is deposited. A processing and metallurgical evaluation was made on LENS processed material fabricated for component qualification tests. A process parameter evaluation was used to determine optimum build parameters and these parameters were used in the fabrication of tensile test specimens to study the characteristics of the interface between LENS deposited material and several types of substrates. Analyses of the interface included mechanical properties, microstructure, and metallurgical integrity. Test samples were determined for a variety of geometric configurations associated with interfaces between LENS deposited material and both wrought base material and previously deposited LENS material. Thirteen different interface configurations were fabricated for evaluation representing a spectrum of deposition conditions from complete part build, to hybrid substrate-LENS builds, to repair builds for damaged or re-designed housings. Good mechanical properties and full density were observed for all configurations. When tested to failure, fracture occurred by ductile microvoid coalescence. The repair and hybrid interfaces showed the same metallurgical integrity as, and had properties similar to, monolithic LENS deposits.

Acknowledgements

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On the Interface Between LENS® Deposited Stainless Steel 304L Repair Geometry and Cast or Machined Components

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Introduction

Laser Engineered Net Shaping™ (LENS®) is a laser metal deposition process developed at Sandia National Laboratories. The process is capable of depositing many types of metal onto substrates using a 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 repair of castings and machined structures. This study focuses on the initial requirement for a precision repair system; the understanding of the interface between the deposited material and the substrate whether that substrate is cast, wrought, or previously deposited LENS material. For this investigation 304L stainless steel was chosen due to its use in weapons systems. Studies performed for the research included a process parameter study to determine the optimum processing window for the material, the creation of a set of representative geometry samples deposited on different substrates, the machining of these samples into tensile test specimens, and tensile testing of the samples followed by metallographic analyses.

Process Parameter Testing

LENS has the ability to not only create geometry, but also, to a certain extent, control the material properties by varying the process parameters associated with the deposition of powdered metal onto substrates. Different process parameters affect the deposition characteristics and material microstructure, therefore varying the material properties. Because of this ability, it is important to test process parameters carefully for each material. The LENS process creates a pool of molten metal where a laser is focused onto a metal substrate. Powdered metal is then blown into the weld pool to create a small deposit. The substrate is moved in a plane perpendicular to the laser axis creating a line of deposited metal. Many lines near each other create a layer, and as the process is repeated with the laser focal point at increasing heights off the substrate, a part is built line by line, and layer by layer. The commonly adjusted LENS process parameters, as shown in Figure 1, are laser power, feedrate of the axes which move the substrate, hatch width, layer thickness, and metal powder mass flow rate. The process variable “hatch width” refers to the distance between parallel passes of the laser as it rasters back and forth to fill in the interior of a geometry. The layer thickness is the amount that the height of the laser focal point is raised from one layer to the next.

A sample coupon size that has been found to work well for process parameter testing is ½ x ½ x ½ inch cubes. These cubes are large enough to exhibit the characteristics of larger block-like solid features, but small enough to be built relatively quickly. For this test, 42 blocks were built with different parameter combinations and the blocks were measured for height and appearance, and then those meeting height and appearance requirements were sectioned and polished to determine the porosity and microhardness of the block's interior. A test matrix of 9 cubes deposited on a ¼" thick substrate is shown if Figure 2 with 3 of the cubes having been sectioned, potted, and polished.

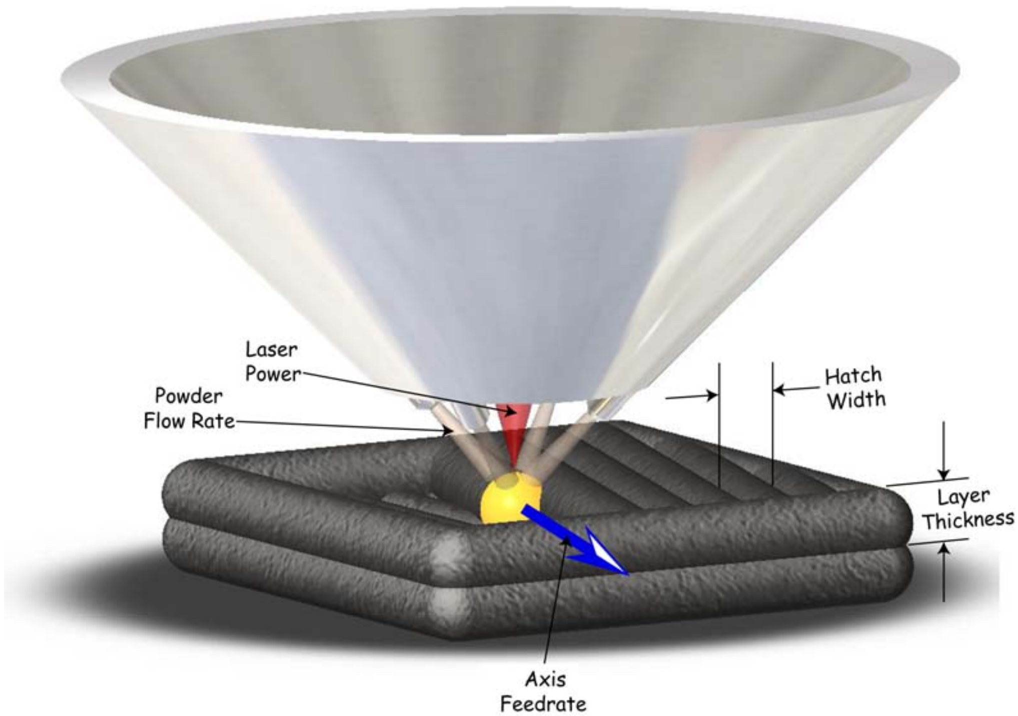

Figure 1. A Model of the LENS Metal Deposition Process Showing Process Parameters That Are Utilized to Select Build Characteristics.

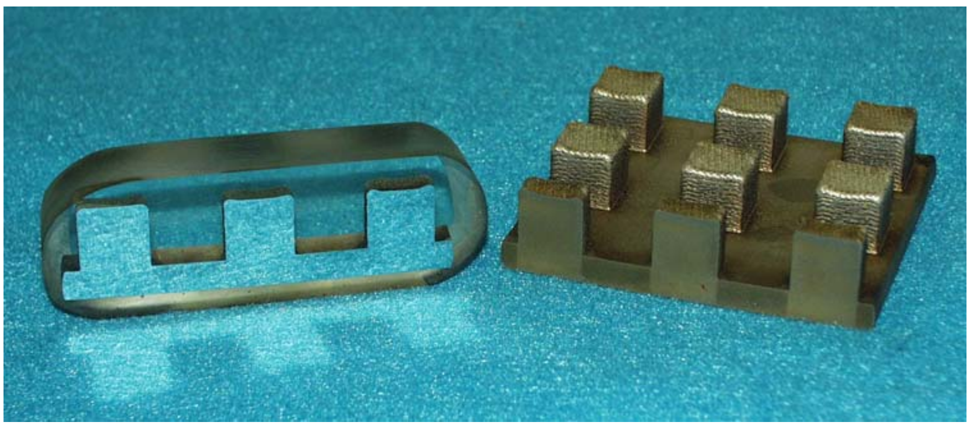

Figure 2. Test Matrix of 9 LENS Deposited Cubes Showing 3 Cubes that Have Been Sectioned, Potted, and Polished for Additional Analysis.

The process parameters that were varied for these tests were the hatch width, layer thickness, powder mass flow rate, and axis feedrate. The values used for each of these parameters are shown in Table 1.

Table 1. Process Parameters and Parameter Values Used in Testing.

Parameter	Values Used in Parameter Test
Hatch Width (inches)	0.020", 0.024", 0.030"
Layer Thickness (inches)	0.025", 0.030"
Powder Mass Flow Rate (grams per min.)	21.8-57.7gpm
Axis Feed Rate (inches per min.)	20ipm, 25ipm, 30ipm

Other machine parameters were held constant for all of the testing. These parameters include layer thickness and the parameters in the feedback system that controls the weld pool area. All cubes were deposited evenly spaced on SS304L substrates ¼" thick and approximately 3x3" square.

Analysis and Results

After all of the cubes had been deposited using different combinations of process parameters, the analysis of each cube included build height and appearance. Though a subjective measurement, the cube appearance has been found to be a good first pass indication of the quality of the build. Good process parameter sets produce cubes with sharp corners, flat tops, and finely visible hatch lines across the top and sides. A second measure is the ability of the parameter set to produce a cube with height equal to or greater than the programmed design height. Because LENS is a near net-shape process and stock will have to be machined away in future processing steps, it is desirable that the outside dimensions of the deposited feature be equal to or greater than the design dimensions leaving machining stock. The cubes that built to or above design height were cut in half vertically using a wire EDM. These cubes were then potted, polished, and examined to determine the porosity of each cube.

The effects of different factors were compared by measuring the part porosity, microhardness, and build height. Due to constraints on resources, 17 of the 42 cubes were sectioned and examined for porosity. Four of the 17 sectioned cubes were also tested for microhardness. As is seen in Figure 2, it is as easy to section and polish an entire row of 3 cubes as it is to use a single cube. This accounts for the difference between the number of cubes that were sectioned and the number that were tested for microhardness.

The porosity was measured by manually counting the number of pores visible in an optical microscope at 50x magnification which gives a visible area of 500 m x 500 m. The pores were divided into two groups, those with diameters in the range of 1-5 m, and those with diameters in the range of 6-15 m. For the samples with the highest porosity, the number of pores was counted for a smaller area and then extrapolated as an estimate of the number of pores in the entire 500x500 m area. The porosity was then compared with the process variables hatch width, axis feedrate, and powder mass flow rate individually. None of these comparisons showed a statistically significant correlation with the porosity. However, it was determined that the number of pores appears to depend on a richness factor. The richness factor is defined as the ratio of the powder feedrate to the product of the hatch width, axis feedrate, and layer thickness. The units of the richness factor are g/in^3 which represents the richness, or the mass of powder per volume to be filled by that powder. As the richness factor increases there is more powder supplied to fill a certain volume of build space. As is shown in Figure 3a, when the richness factor is higher, the number of large pores decreases, but the number of small pores increases.

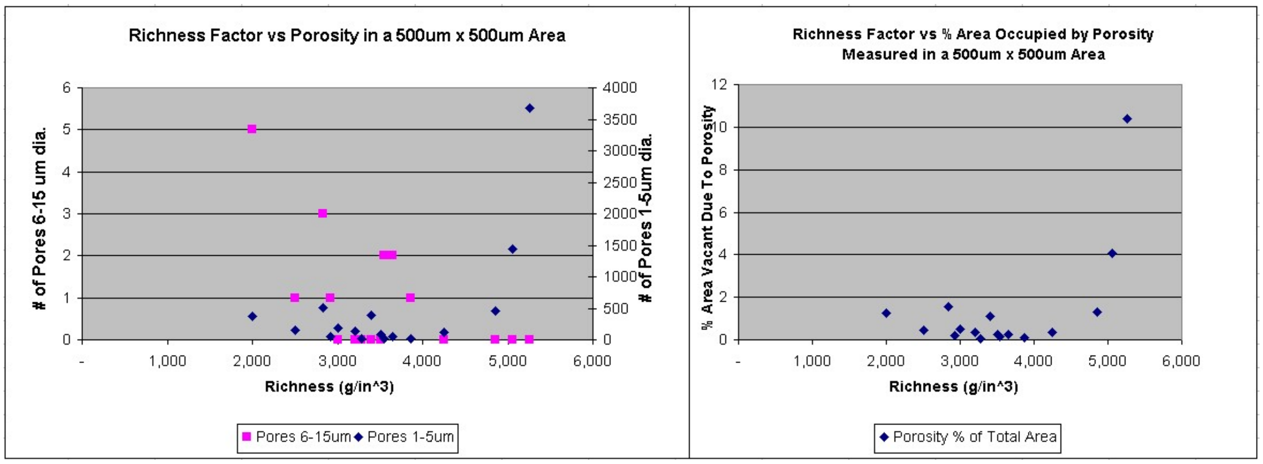

Figure 3. Richness Factor Compared with Porosity by Pore Size(a) and by Percent of Total Area Consumed By Pores(b).

The proposed explanation is that at high powder flow rates, the weld pool is overwhelmed with powder and is not able to fully melt all of the incoming powder causing small voids in the material. When the richness factor is low, there is a shortage of powder and the weld pool is somewhat starved for powder. In previous work, it has been noted that the melted powder attempts to draw into a ball due to the surface tension of the material. It appears that the powder starvation in the weld pool allows the material to pull apart leaving the larger 6-15 m voids. It is important to note that even in the sample with the greatest number of large pores, there were still only 5 large pores in the 500 m x 500 m area. The majority of the area vacated due to porosity is due to the small pores. The small pores occupy between 0.07% and 10% of the total area in the samples as is shown if Figure 3b. Comparing the blue diamonds in graphs 3a and 3b, it is evident that the majority of the area vacated due to porosity is due to the smaller pores.

The microhardness measured in the 4 samples was found to be fairly consistent between the samples with no assignable variation due to the deposition factors. The microhardness was measured in 5 locations on each of the 4 samples. The average hardness of ranged between 176 and 195 Vickers hardness as shown in Figure 4, but the one standard deviation error bars reveal that the mean values of microhardness for each cube are not significantly different than the other cubes.

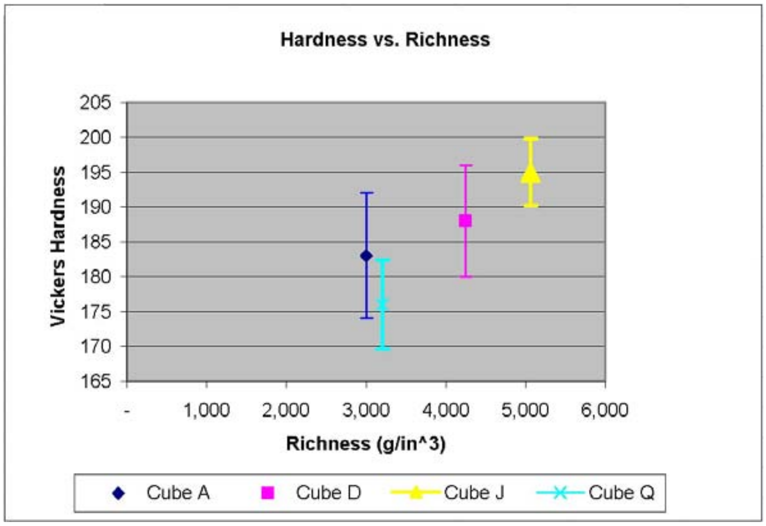

Figure 4. Graph of Vickers Hardness for Different Richness Values as Measured On 4 Cubes at 5 Locations Per Cube.

From the results of the parameter tests, the values of 0.020" hatch width, 0.020" layer thickness, 20ipm axis feedrate, and 23g/min powder flow rate were chosen. This correlates to a richness factor of 2925 where the porosity is low and the build height was 0.005" taller than the design height.

Depositing of Tensile Test Coupons Using LENS

The testing of LENS deposited configurations continues as a portion of a project to utilize LENS capabilities in the repair and modification of castings and machined components for LEP qualification development tests. For LENS to be utilized in this manner, it is first necessary to have an understanding of the interface between LENS deposited material and the component upon which the material is being deposited. To study this interface, a set of tensile test samples representing a spectrum of features of candidate W80 and W76 components was created using LENS to deposit 304L stainless steel. The deposition occurred at the optimum process parameters as detailed above and represented 3 different deposition conditions: 1) Complete or monolithic LENS part builds, 2) Hybrid LENS builds onto a wrought/cast substrate, and 3) Repair or re-construction LENS builds on previously deposited LENS material. The samples were designed so that flat-dog bone and round tensile specimens could be machined from the deposited LENS material. The lens deposited samples are shown in Figure 5 where the striped regions represent the layers of deposited LENS material and the grey regions represent wrought substrates. The orientation of the stripes in the white LENS material represents the deposited layers.

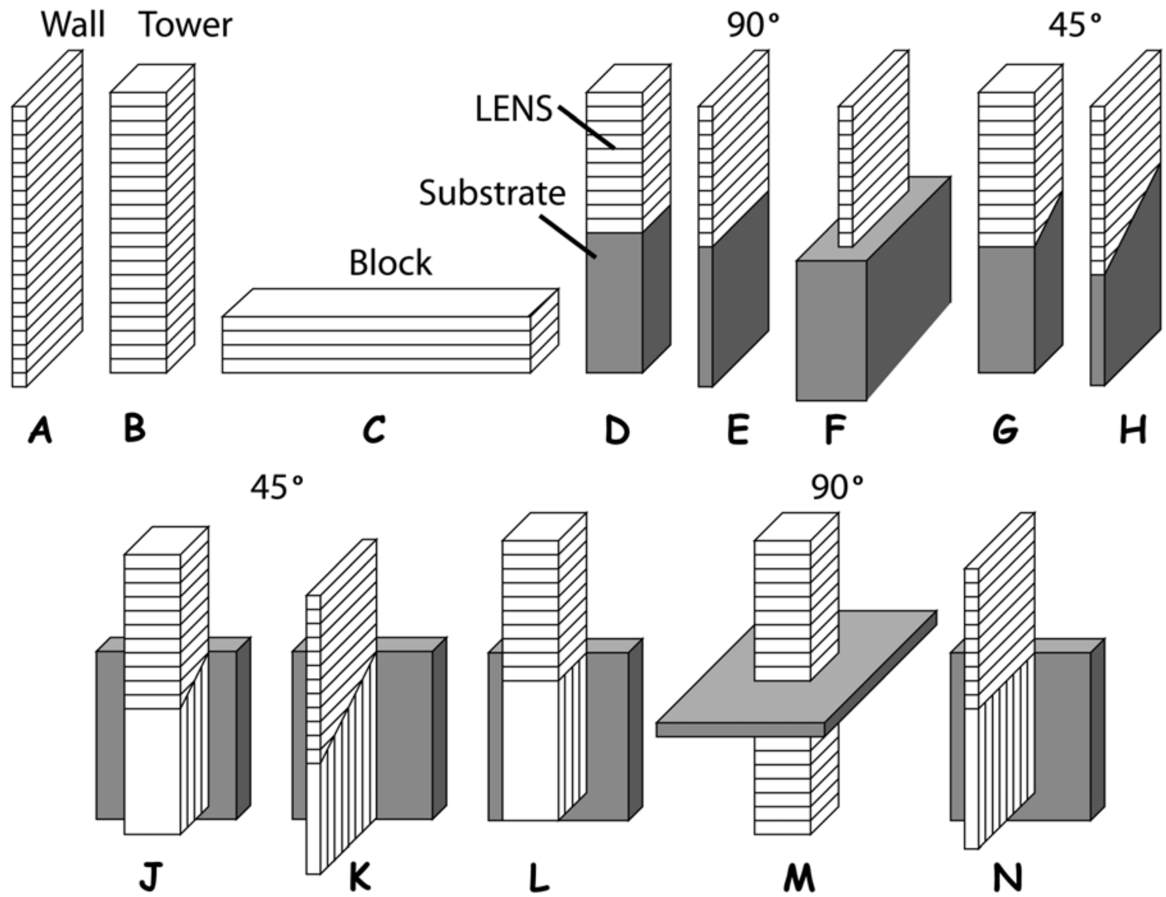

Figure 5. Schematic of 13 Different Types of LENS Deposited Tensile Test Specimens Representing Repair and Modification Geometries.

The deposited configurations included 2 primary classes of components: the Block/Tower class and the Thin Wall class. The LENS classes can be further divided by the shape of the substrate onto which the material was deposited including thin walls deposited on thin walls (types E, H, K, N), thin walls deposited on thick Block/Towers (type F), and towers deposited on thick blocks (types D, G, J, L). The Block/Towers were 0.5" square by at least 2 inches tall. The thin wall builds were 1 inch wide by 0.125 inches thick and 2.5 inches long.

The tension samples can also be divided into 3 groups based on the method of creation of the substrate materials at the interface. The first group is the fully monolithic LENS deposited parts (types A, B, C) which have no interface and were used as a control in the testing. The second group contains an interface between LENS deposited material and a wrought material substrate (types D, E, F, G, H, M). The third group has an interface between two sets of LENS material deposited in different orientations (types J, K, L, N). To make the samples more realistically representative of 3 dimensional LENS repair and modification, the angle of the interface was tested at both 90º (types D, E, F, L, M, N) and at 45º (types G, H, J, K.) A 90º interface causes the newly built layers to be parallel to the interface which is a good means of testing inter-layer adhesion. The 45º interface causes each LENS deposited layer to be slightly longer than the previous layer. Thus, each layer's interaction with the interface contains an "end" where there is a step change in build height which must be filled by the next layer. The ends of layers might be suspected as being the most susceptible region for porosity and bond weakness. An additional test is shown in part M in which the substrate is integral to, and becomes part of, the final component. This sample has two interfaces created at different times.

For the Block/Tower or thick features, sample sets B and C represent monolithic vertical and horizontal LENS builds respectively. Sample sets D and G represent interfaces of a LENS deposit onto a bulk wrought substrate, the former oriented 90 and the latter 45 to the build direction. Sample set M represents interfaces of a LENS deposit onto opposite sides of a bulk wrought substrate at 90 . Sample sets L and J represent interfaces of a LENS deposit onto a previously fabricated LENS deposited substrate, the former with an interface oriented 90 and the latter with an interface oriented 45 to the build direction.

For the Thin Wall Builds, sample set A represents monolithic deposits. Sample sets E, and H represent LENS deposits on thin walled wrought substrates with 90 and 45 interfaces respectively, and set F represents a thin wall deposited on a more massive substrate. Sets K and N represent LENS walls deposited onto previously deposited thin LENS walls at 45 and 90 interfaces respectively.

The coupons built as tension test samples were deposited using the parameters determined in the process parameter test. These parameters were 0.020" hatch width, 0.020" layer thickness, 20ipm feedrate, 23g/min powder flow rate, and a laser power controlled by the automated weld pool area control between 300-60 Watts for the Block/Tower geometry. The thin wall structures were built with the same process parameters except that the powder flow rate was 20.3g/min and the laser power modulated between 230-495 Watts. The hatch travel direction for each successive layer was rotated 105 degrees. On the thin wall samples, the fewest number of line scans per layer is 5 (3 hatch + 2 border) and the maximum number of scans is 49 (47 hatch + 2 border), depending on deposition direction. For the chosen test types, either 2 or 3 tensile coupons were created. The LENS deposited samples are shown in Figures 6 and 7.

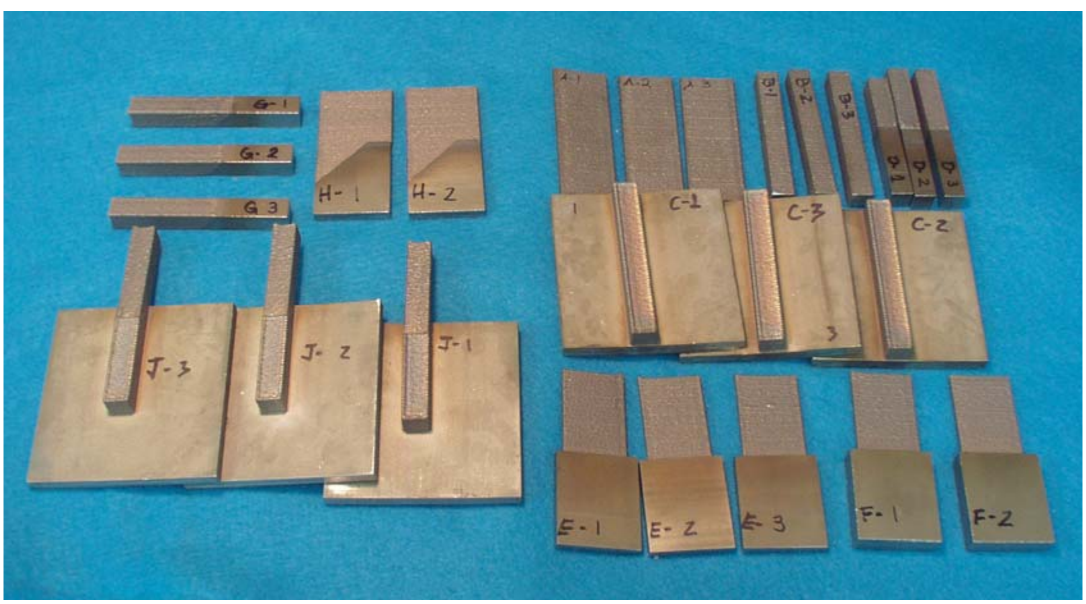

Figure 6. LENS Deposited Sample Types A-J for Machining Into Tensile Specimens.

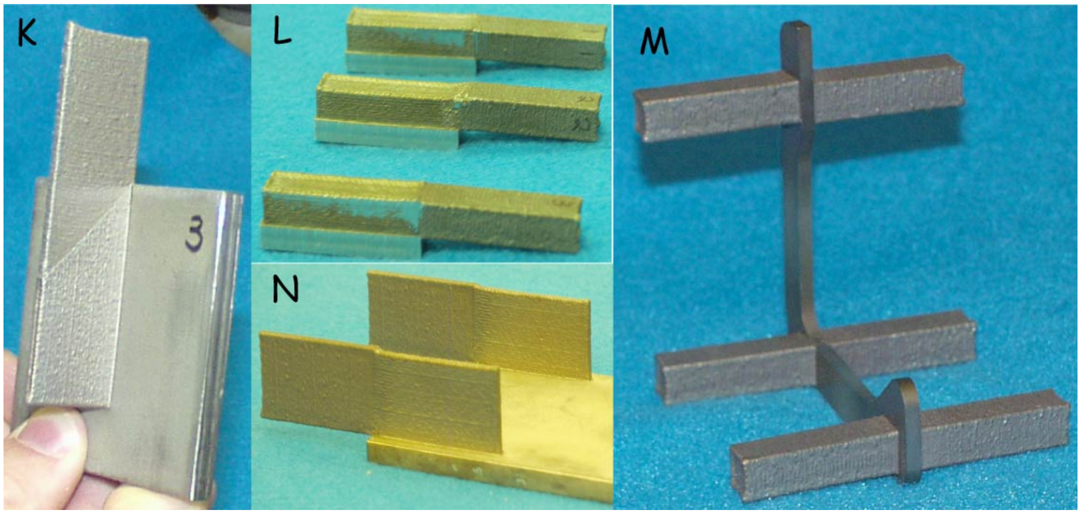

Figure 7. LENS Deposited Sample Types K-N for Machining Into Tensile Specimens.

As can be seen in Figures 6 and 7, not all of the specimens were deposited perfectly, especially with respect to alignment. Most of the misalignments were due to difficulties fixturing a previously deposited LENS sample for subsequent processing due to deflection of the substrate. However, the misalignment of the deposited sections was seen as acceptable due to the machining of each sample into a tension test coupon. For the tension test, the parts were machined significantly as shown in Figure 8, especially in the area of the interface. At these areas, the parts were machined to have significantly reduced cross section to focus the stress around the interface. This reduction in cross section effectively machined away any misalignment. Careful notes were taken during the LENS building process especially to record any processing anomalies that might have an effect on the strength of the parts and interfaces between sections.

Figure 8. LENS Deposited Tensile Specimens Machined into Round and Flat Tension Test Coupons

The samples were made from gas atomized 304L stainless steel powders. Chemical and size analysis was supplied by the vendor's certifications and is listed in Table 2.

Table 2. Certification Data for 304L Powders Used to Fabricate Samples.

Characteristic	**Heat 88855**	**Heat 88594**
Alloy Name	Micro-Melt 304L	Micro-Melt 304L
Manufacturer	Anval	Anval
Supplier	Carpenter Powder Products	Carpenter Powder Products
Nominal Size (mesh)	-140/+325	-140/+325
Nominal Size (microns)	-100+44	-100+44
Chemical Analysis	Heat 88855	Heat 88594
C	0.010	0.012
Si	0.48	0.55
Mn	1.48	1.46
P	0.010	0.010
S	0.005	0.005
Cr	18.5	18.4
Ni	9.6	9.5
Fe (bal)	69.9	70.1
Cert. #	9417-1	6331-1
Cert. Date	12/10/2002	12/5/00

Tension Test Experimental Procedures

The LENS deposited samples were sectioned by EDM for metallographic mounting and/or for further machining into tensile bars for mechanical testing. The metallographic samples were taken from the top of each LENS deposited region with the cut oriented perpendicular to the final layer deposition direction. This cut provides a view that allows an assessment of the melt pool size, relative amounts of overlap of successive deposit traces into the plane of the sample, and amount of re-melt of each successive layer. 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.

Metallographic samples were mounted in clear epoxy and prepared using standard metallographic grinding and polishing techniques. Etching was done using an electrolytic oxalic etch at 3 V for 15 seconds. Samples were examined optically for porosity to assess their metallurgical integrity, and the amounts of re-melt with each pass and/or layer. A qualitative assessment of the fracture behavior was done using SEM observations of one half of a subset of the fractured tensile samples.

Results and Discussion

Observations are made for each of the basic types of deposition: 1) Complete or monolithic LENS part builds, 2) Hybrid LENS builds onto an integral wrought/cast substrate; and 3) Repair or re-construction LENS builds on damaged or salvaged housings. The tensile results for smooth bar samples are shown in Figures 9 and 10. The values listed in these figures are ultimate tensile strength (UTS), tensile yield strength (YTS), ductility measured by tensile elongation (et), and ductility measured by reduction in area (RA).

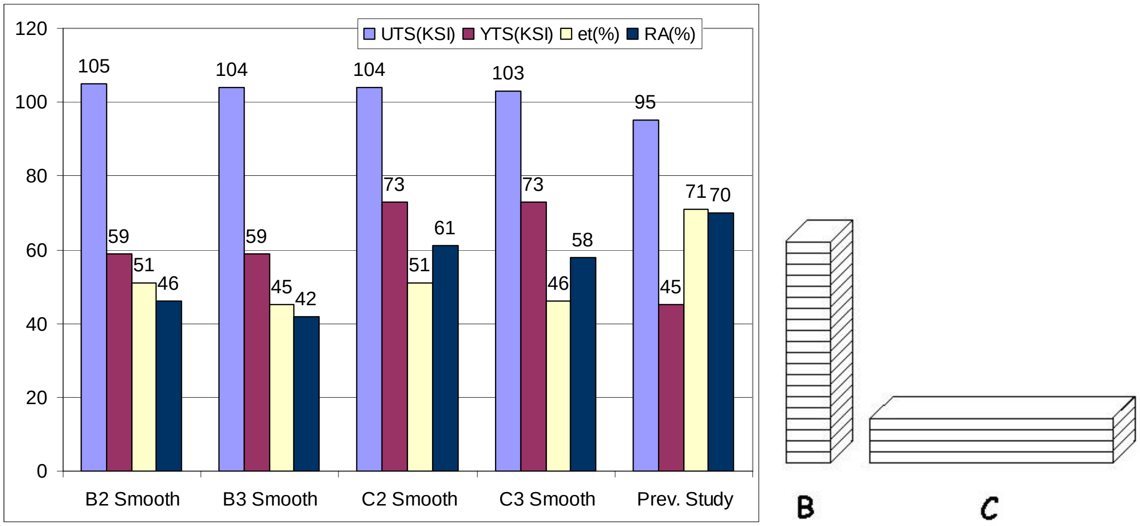

Figure 9. Mechanical Properties of Monolithic LENS Builds Comparing Block/Tower Samples (Types B and C) to a Previous Study for 304SS.

Figure 8 shows the Monolithic LENS build properties. The yield strengths for the vertical Block/Tower builds (type B) were 59 KSI, and ductility measured by elongation of 45% and 51%, while ductility measured by reduction in area were 42% and 46%. Yield strengths for the horizontal Block/Tower builds (type C) were 73 KSI, and ductility measured by elongation ranged from 46% to 51%, while ductility measured by reduction in area were 61% and 58%. The yield strengths for a previous in-house study of LENS deposited 304 stainless steel tower builds (labeled previous study in Figure 9) were only 45 KSI, but with a higher ductility of about 70%, for both elongation and reduction of area.

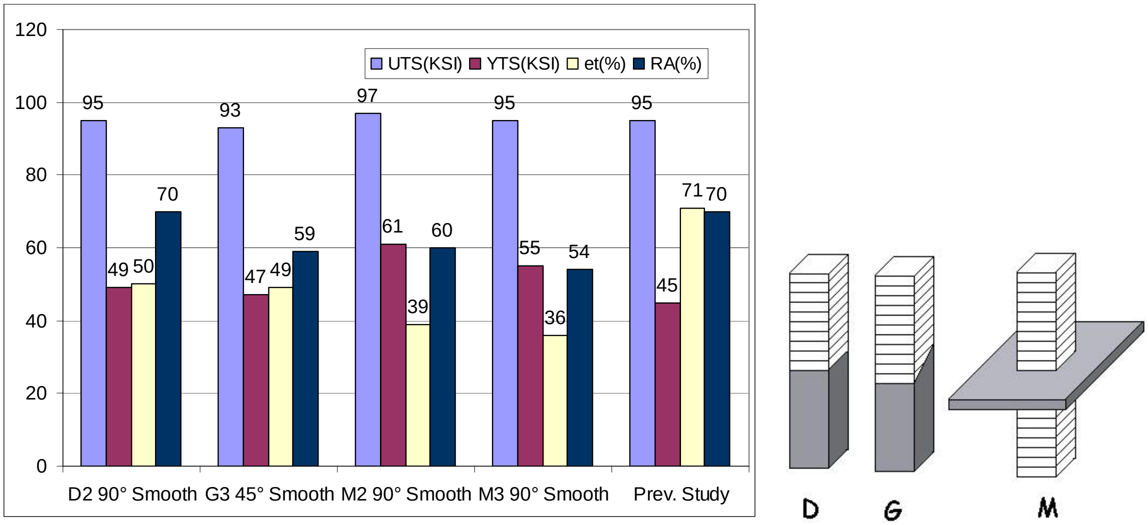

Figure 10. Mechanical Properties of Hybrid LENS Block/Tower Builds on Wrought Substrates Comparing Sample Types D, G, and M to a Previous Study for 304SS.

Figure 10 shows properties of the Hybrid LENS built samples on wrought or cast substrates. The yield strengths for the hybrid LENS builds on wrought substrates ranged from 47 to 61 KSI, and ductility measured by elongation ranged from 36% to 50%, while ductility measured by reduction in area ranged from 54% to 70%. The yield strength measured for the single interface samples, types D and G, was lower than the yield strength for the double interface type M coupons. The single interface values are comparable to those of a previous in-house study of monolithic LENS deposited 304 stainless steel tower builds. However, the ductility as measured by elongation was lower. There is an indication that the orientation of the interface may affect the measured ductility, but not the strength (higher for 90° than for 45°).

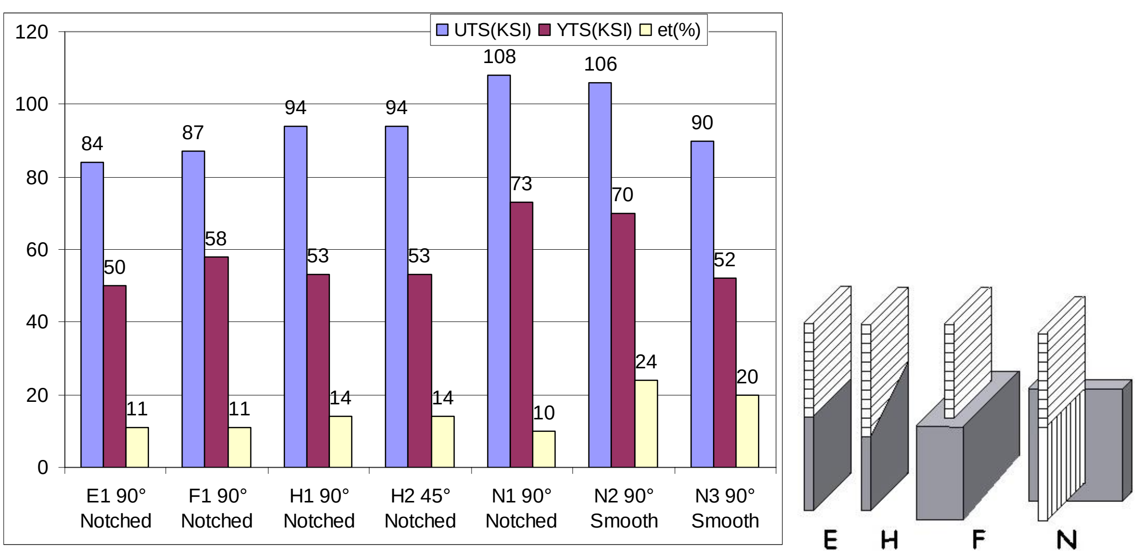

Figure 11. Mechanical Properties of Hybrid LENS Thin Wall Builds on Wrought Substrates Comparing Sample Types E, H, and F to Sample Types N Deposited on LENS Substrates.

Figure 11 shows the tensile results for hybrid LENS thin wall builds on wrought or cast substrates using notched flat tensile specimens. For the flat specimens, much lower loads were needed to reach the yield and fracture strengths, and consequently this data has more uncertainty because it used the lower end of the load cell range. Sample types E and F represent the effects caused by different masses of the substrate for a thin wall/substrate interface, and therefore different cooling rates at the interface. The more massive substrate interface had a slightly higher yield strength, but the same ductility as measured by elongation. Sample set H had both a 90 and a 45 interface, with the 90 interface having a lower yield strength and the 45 interface having about the same strength as the E and F sets. For reference, the notched samples are compared to the LENS on LENS thin wall build set N for which both notched and smooth samples were tested. The smooth samples of type N have total elongations greater than 20%, compared to the notched sample with 10%. Again, the values for yield strength and total elongation of the notched samples are not valid values but give relative indications of differences between samples. We see here that the strengths of interfaces between hybrid LENS on wrought substrates is lower than the strengths of interfaces between LENS on LENS substrates. The differences in ductility between the two types of build may be due to the specimen geometry, but determination was outside the scope of this study.

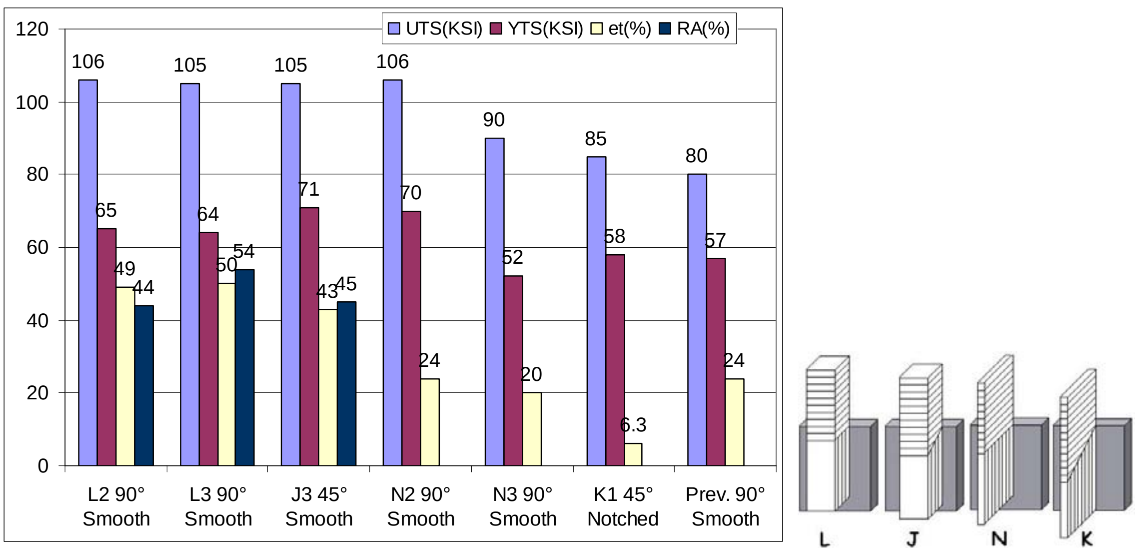

Figure 12. Mechanical Properties of LENS Builds on Previously Deposited LENS Substrates of Types L and J (Block/Tower) Compared to N and K (Thin Wall) and a 316 SS Thin Wall From a Previous Study.

Figure 12 shows the properties of LENS builds on previously built LENS substrates, comparing Block/Tower builds (types L and J) to Thin Wall builds (types N and K). Round tensile bars were used for the Block/Tower builds and thin flat tensile bars for the Thin Wall builds. Yield strengths ranged from 64 to 71 KSI for the Block/Tower builds and from 52 to 70 KSI for the Thin Wall builds. As was the case for monolithic LENS samples, the strengths of the two different types of build as measured on two different sample geometries were similar, but the total elongations were lower for the flat specimens. The values compare favorably with monolithic LENS deposited material.

In general, the strength of the smooth round tensile bars is about twice that of annealed material, but without any significant difference in ductility. These values represent enhancements to annealed 304L stainless steel and give designers a higher strength material, without needing to work it or have to switch to age-hardenable compositions that would require post shaping heat treatments. While not the same range of strengths as alloys like PH13-8 Mo, the LENS processed material offers a lower cost alternative which would also eliminate the need for heat treatment.

The microstructure of all samples contains features at two size scales. At the largest size scale are boundaries that result from overlapping passes in the same plane (inter-pass boundaries) as well as boundaries formed by successive layers (interlayer boundaries). These correspond to the molten metal pool size, which depends upon the deposition conditions. The microstructure shows two irregularities: 1) porosity is larger than previously observed in other LENS builds, and oxide inclusions are present, and 2) the cross-sections of the melt pool suggest that the closed loop control for keeping the melt pool constant was not performing as effectively as it has for previous studies.

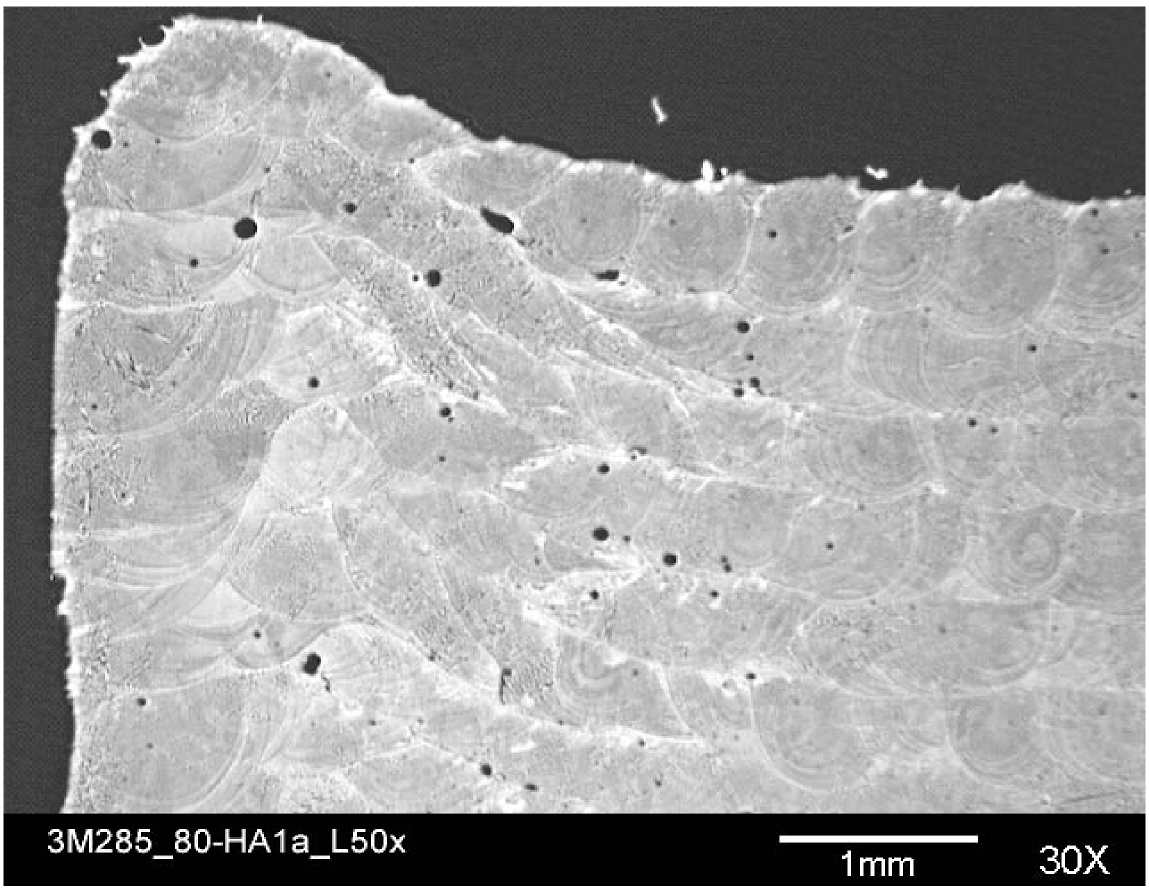

Figure 13. Cross Section of the Top Layers of a Block/Tower Deposit of Type B.

Samples are essentially fully dense, but have small amounts (less than 1%) of closed porosity and some trapped non-metallic particles. The pores and trapped particles are generally similar in size. The cross sections (see Figure 13) indicate that control of the melt pool during deposition was not able to maintain a flat profile. The edges have an additional build-up over the height of the interior of the parts.

The microstructure in the center of the samples appears to be more uniform than that observed at the top layer. Because of the programmed orientation difference in deposition direction from one layer to another, the periodicity of layer orientation is twelve layers as shown in Figure 14. In general the individual line deposits show reasonable uniformity and layers exhibit good flatness in the center of the cross-sections. Figure 15 shows the microstructure in the center of a type N Thin Wall LENS-on-LENS deposit. In the thin wall structure, there are approximately 5 "fill" passes per layer.

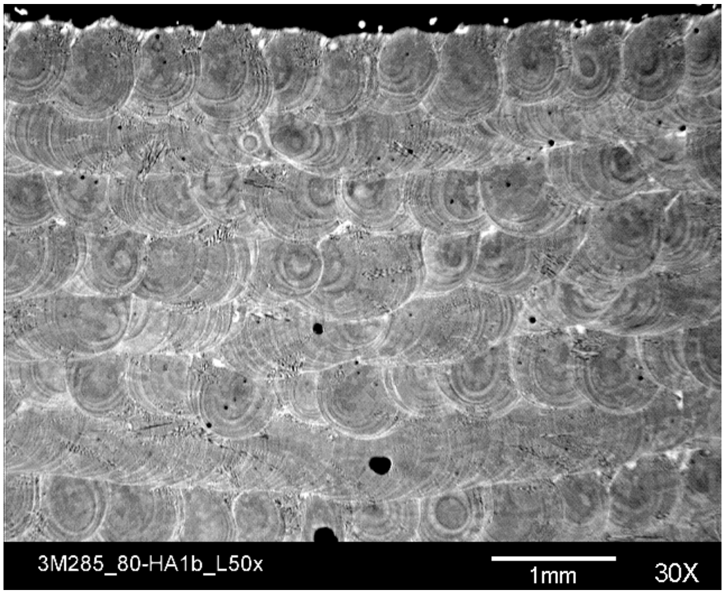

Figure 14. Cross Section of the Top Layers of a Block/Tower Having a 105º Orientation Difference Between Successive Layers.

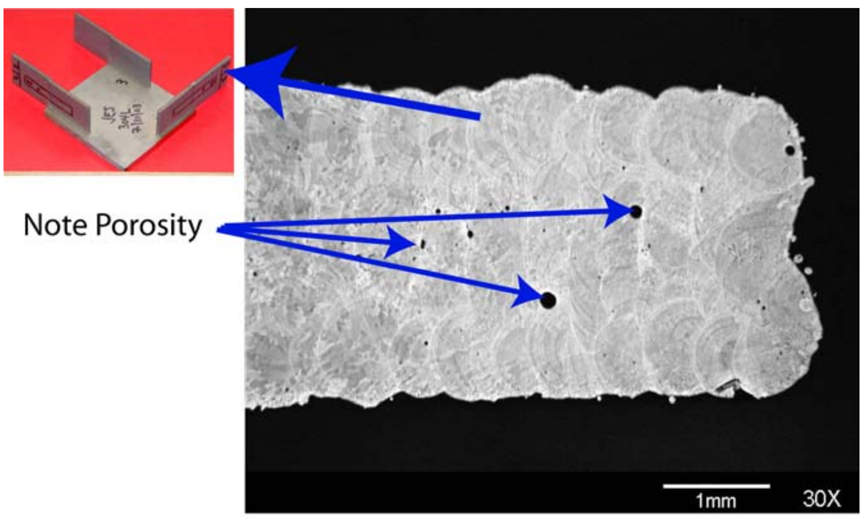

Figure 15. Cross Section of the Top Layers of a Thin Wall Deposit of Sample Type N Showing About 5 Passes Per Layer.

At higher magnifications, finer microstructural features which are likely δ-ferrite are observed with multiple orientation variants at the interfaces between successive overlapping line passes and layers. The ferrite has a lath-like morphology that gives a needle-like appearance if viewed transversely. There is both an epitaxial solidification component as well as the more orthogonal component of the interface microstructure, as shown in Figure 16. In general, there is complete filling of void space for all samples examined. The occasional closed pores do not appear to strongly impact the tensile strength or ductility, and it is believed that porosity levels can be reduced through further process optimization.

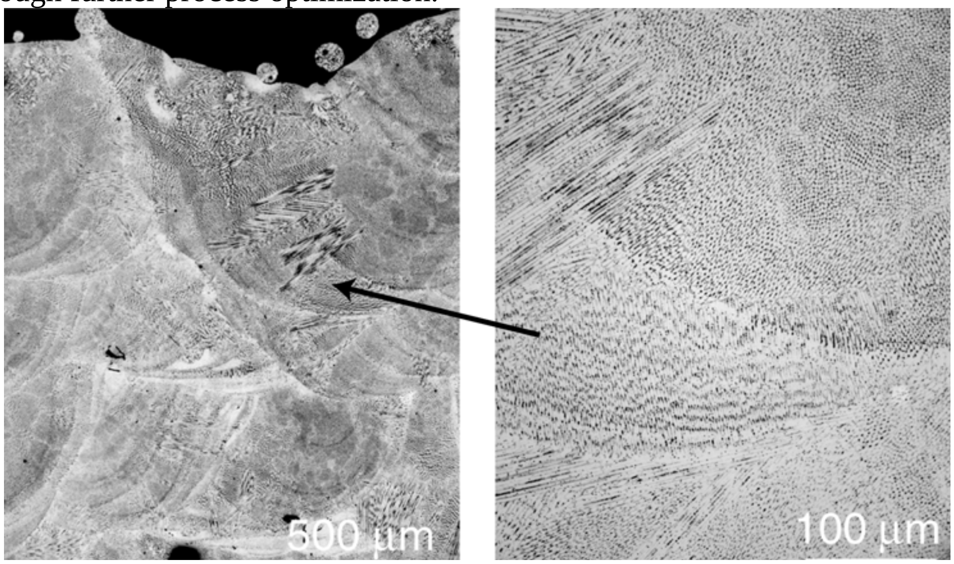

Figure 16. Details of Microstructure at the Top of a Type N Thin Wall Sample.

A small fraction of the samples had fracture surfaces that indicated possible manufacturing defects. These are probably a result of a mismatch between the size of the molten pool and the settings for spacing of the line deposits or layer thickness. Inadequate metallurgical bonding would occur due to lack of fusion between subsequent layers. Adjusting the settings through further process schedule development or employing appropriate closed loop process control typically eliminates this type of defect.

Fracture surfaces from several of the various test samples are shown in Figures 17-20. The fracture surfaces showed some unusual features for several samples, apparently associated with inadequate lack of fusion across interfaces associated with the interrupted deposition of material required to examine repair scenarios and extended cantilever builds.

Fracture surfaces in general consist of macroscopic cup-cone fracture, and a microscopic ductile dimpled fracture mode. These features are similar to that observed in wrought material fracture, except that the LENS deposits also occasionally exhibited secondary features corresponding to irregularities in deposition layer spacing.

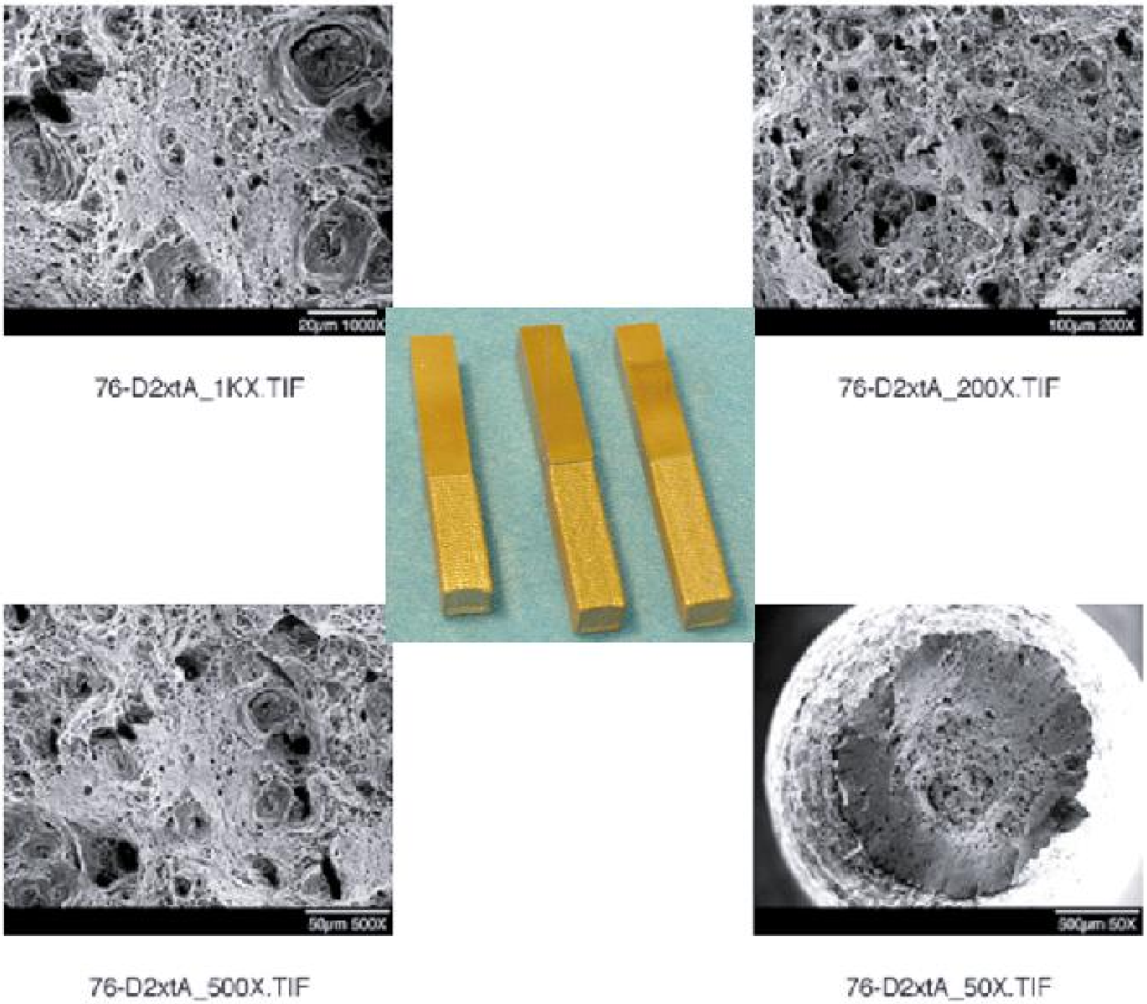

Figure 17. Fracture Surface of Block/Tower Deposit Type D.

Figure 17 shows the ductile fracture characteristic cup-cone features in the low magnification images and ductile dimpled features at higher magnification. The ductile dimple features are seen in a mixture of dimple sizes with some evidence of secondary cracking. The ductility of this sample was 50% total elongation.

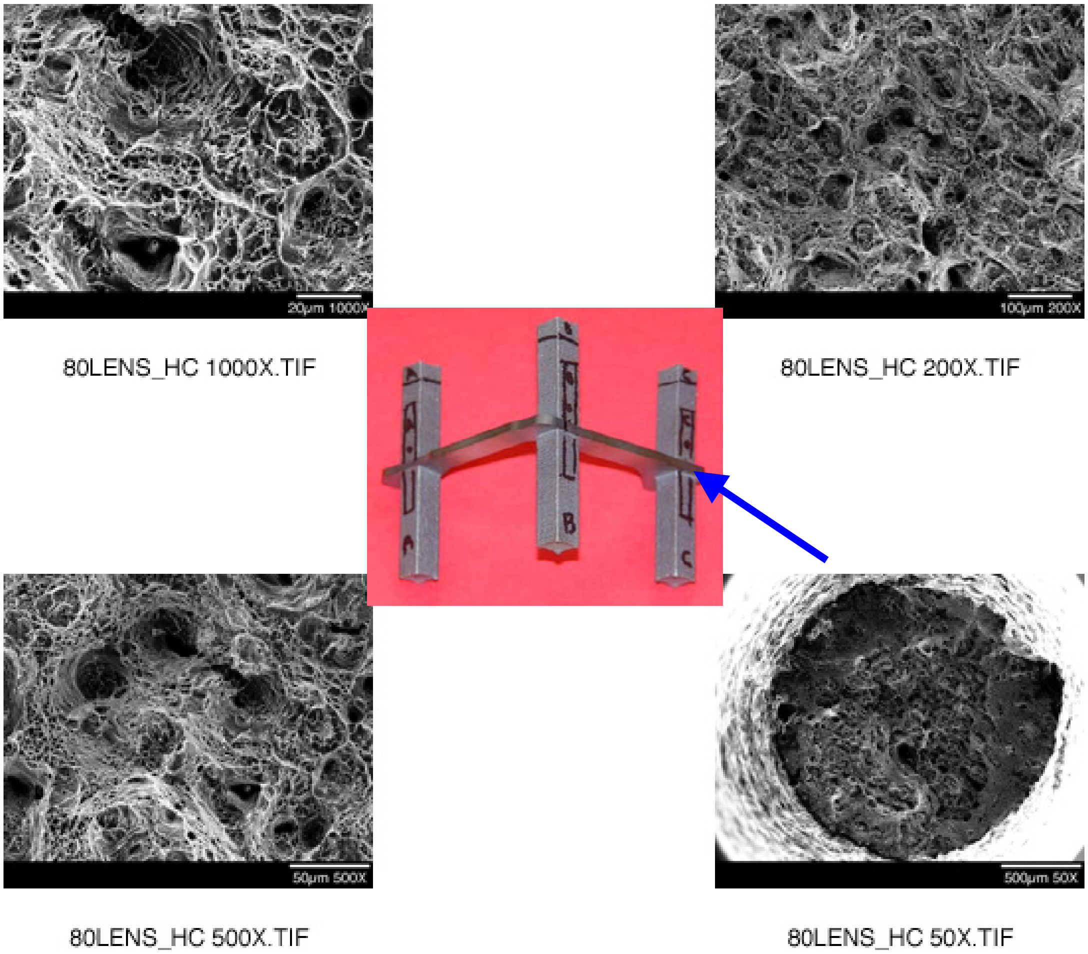

Figure 18. Fracture Surface of a Type M Hybrid LENS Build on Both Sides of a Wrought Substrate.

Figure 18 shows the fracture features of a type M LENS deposit that was built on both sides of a wrought 304L substrate. The fracture features showed many similarities to those of the type D fracture features of Figure 17. The ductility for this sample type, was 36% total elongation. Figure 19 shows the fracture features for a type L Block/Tower build. The fracture features are again very similar to those seen on type D samples. Figure 20 also shows the fracture features of a type L LENS on LENS Block/Tower sample. The figure shows defects seen in several samples that are thought to be due to lack of fusion. In the case of Figure 20 (type L), the features correlate to inter layer spacing and were caused by disruptions during the deposition process. The ductility of this sample was still 49% total elongation, indicating that measured ductility does not significantly reflect changes in the nature of the fracture features.

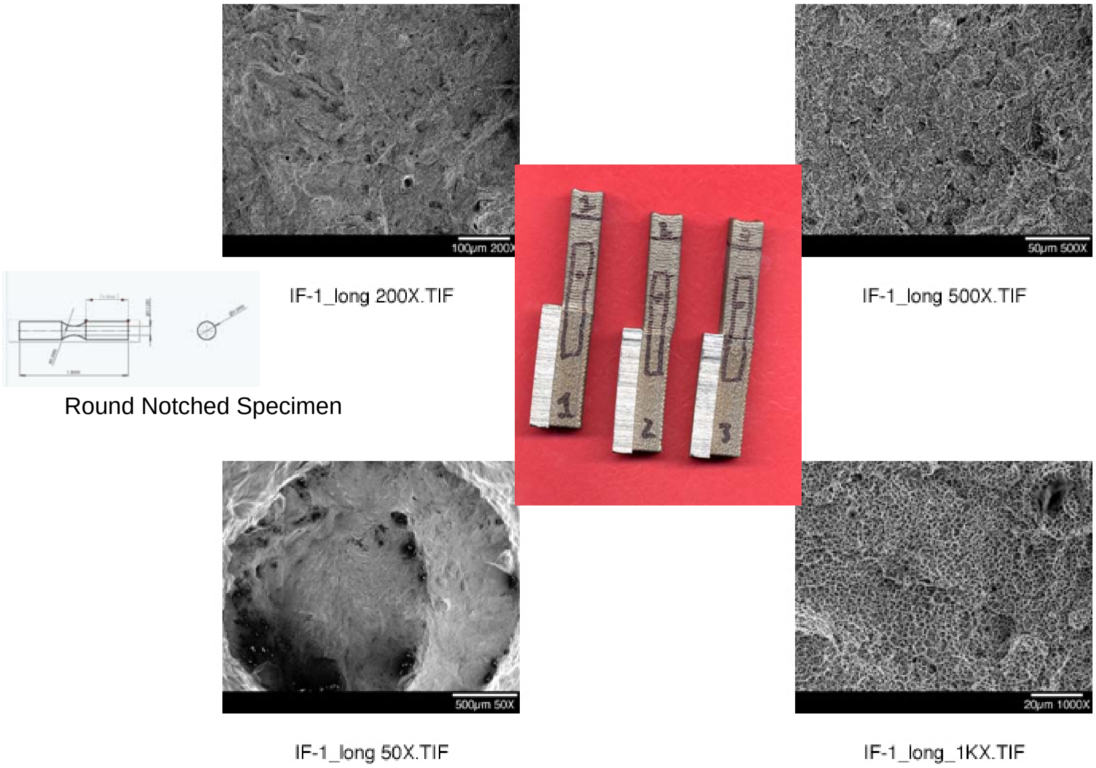

Figure 19. Fracture Surface of a Type L Block/Tower LENS Build.

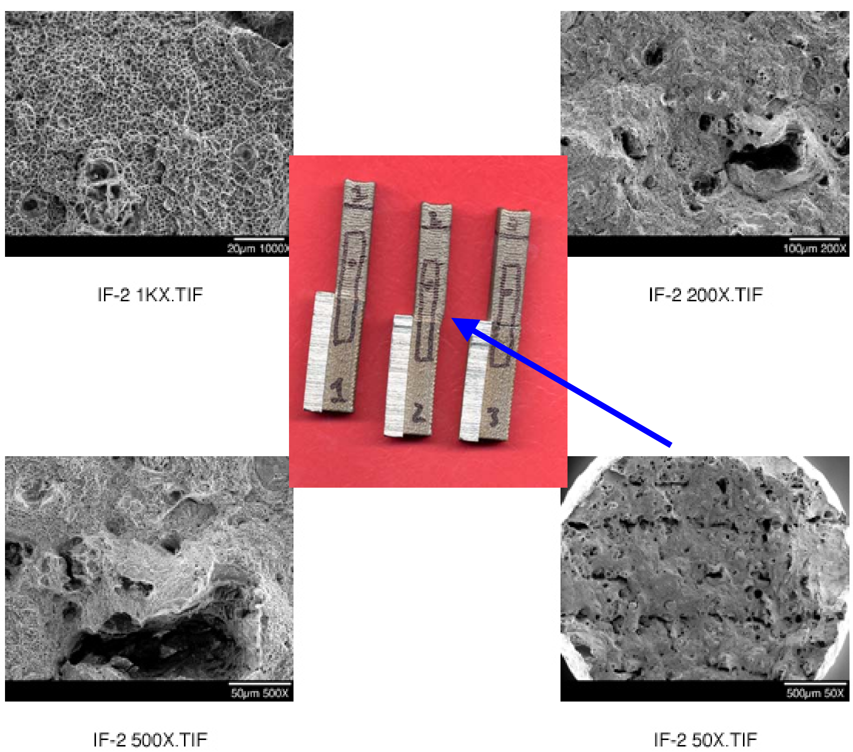

Figure 20. Fracture Surface of Type L LENS on LENS Block/Tower Showing Defects Due to Lack of Interlayer Fusing

Summary and Conclusions

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 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.

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