REPEATABILITY ANALYSIS OF 304L DEPOSITION BY THE LENS® PROCESS

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Abstract

Sandia National Laboratories is currently engaging in an effort to qualify Laser Engineered Net Shaping™ (LENS®) as a repair and modification process for high rigor metal components. As part of that effort, the LENS team has conducted a process repeatability test to help identify variation within the system. This test utilized 304L stainless steel which is a commonly used material at Sandia. Over the course of 12 weeks, 3/8"x3/8"x2" towers were built in sets of 3 with a total of 30 towers completed. A random sampling of 10 of these towers (1 from each set of 3) had been identified before depositing the towers, and these towers were used for tensile testing and metallographic testing. The testing showed the ultimate and yield strengths of all samples to be well above those of annealed 304L. This is expected because of the rapid melt pool solidification present in the LENS process and the resulting grain refinement. The ductility, which usually remains on par with annealed 304L, was found to be lower. The final cause of this loss of ductility was determined to be inter-layer separation due to loose wires in the closed loop melt pool control system.

Introduction

In an effort in gain greater utilization of the Laser Engineered Net Shaping™ (LENS®) process, Sandia National Laboratories is pursuing the qualification of LENS for the repair/modification of high rigor metal components. The authors are attempting to gain enough information regarding the utilization of LENS for repair and modification processes so that design engineers can select LENS as the method of choice for certain applications. To achieve this goal, it is imperative that design engineers and product engineers have the confidence that LENS produced parts or repairs will withstand the challenging environments experienced by these parts. One aspect of the qualification is the need for repeatability testing to give confidence in the process. To that end, Sandia engineers have begun a set of repeatability tests to identify variation within the LENS system.

Depositing the Test Samples

In order to assess the repeatability of the LENS process at Sandia National Laboratories, a repeatability test was performed. The repeatability test samples were 3/8"x3/8" towers built to a final height of 2". The 3/8"x3/8" size is large enough to be indicative of thick builds (as opposed to thin wall builds) while also being small enough to be built in a reasonable amount of time. The material used is 304L Stainless Steel in the size range of -100/+325 mesh. Each layer of the tower was built by depositing the border and then filling (hatching) in the interior of the square in a rastered motion. The layer thickness (as determined by the incremental steps of the Z axis between layers) was 0.020", the hatch spacing was 0.020", and the axis federate was 22 in/min. The hatch direction of each layer is rotated 105° from the layer below which causes any parallel passes to happen after 12 layers and most hatching irregularities to repeat only every 24 layers. The laser power was controlled by a closed-loop melt pool area controller (MPAC) and the focal point was embedded 0.175” below the surface of the material. All samples were made using the same M&G code program which was created by Damocles, a model based, automatic code generator developed at Sandia National Laboratories.

The towers were deposited in sets of 3 with all 3 towers being built on a single 0.25” thick, 304L stainless steel substrate. Ten sets of 3 samples each were deposited as time allowed over the course of 12 weeks. On some days, 2 sets of samples would be deposited in succession. Other sample sets might have a week or more between them. While little effort was made to schedule the depositing of the samples at specific times, the authors attempted to deposit sample sets before and after particularly large builds, the longest being 18 hours long and all builds during this period lasting in excess of 6 hours (except for the repeatability samples). Over the course of this 12 weeks, the laser operated in excess of 120 hours, the glove box atmosphere was brought down (i.e. the purified argon atmosphere was released) for maintenance and cleaning on multiple occasions. The laser had routine maintenance and the powder feeders were rebuilt to replace the seals. Many other parts were built during this time as well, though all were 304L. All of this was done to assess the repeatability and control of the process over a significant period. The repeatability of the machine has always been a concern with “tribal knowledge” speculating that the process varied from day to day, but with no data to back up this assertion. Because the machine is a research grade machine, there were concerns that some process parameters might not be adequately controlled.

Each sample was given an identification number of the ABC format where A (1-6) denotes the build day, B (1,2) denotes whether the sample is from the first or second set of the day, and C (1,2,3) denotes the sample order within the sample set of 3. For example, 622 would be the sixth day of depositing repeatability samples, the second set of the day, and the second sample deposited in the set.

During the depositing of the samples, several anomalies were noted in the builds. These included a condition in which the laser power was driven to its maximum value by the closed-loop melt pool area control system. This occurred at seemingly random intervals and during the build of these towers, no cause for this variation was identified.

Sample Testing

Before the repeatability test began, a random set of 10 samples was chosen for evaluation. One tower from each sample set of 3 was selected for testing. For these 10 samples, the top ¼” was cut off of the tower and sectioned, potted, and polished. The sectioning was done perpendicular to the direction of the hatch on the top layer to allow true measurements of weld pool size. If the sectioning is done at an angle to the hatch, the width of the layers in the section is projected and doesn’t give a true measurement of hatch width. The bottom 1.75” of the tower was turned on a lathe to create a tensile bar specimen with 0.125”diameter gage section with 0.62” gage length. The tensile bars were pulled at a rate of 0.05in/in/min. Values were recorded for ultimate and tensile strengths as well as ductility measured by reduction in area and tensile elongation.

Tensile Testing Results

The tensile testing results showed some expected characteristics and one unexpected characteristic. Typically, LENS deposited material has a higher strength than annealed material due to grain size refinement that occurs during the rapid solidification of the melt pool. By this method, there is often no loss of ductility as is often experienced by other strengthening methods like cold working.

The tensile testing confirmed these expectations with ultimate tensile strengths and yield tensile strengths well above the specification value for annealed 304L stainless steel. Table 1 shows the values for strengths and ductility as set in the specification of annealed 304L material. Figures 2 and 3 show the measured ultimate tensile strength and tensile yield strength. Figures 4 and 5 show the measured ductility as determined by tensile elongation and reduction in area.

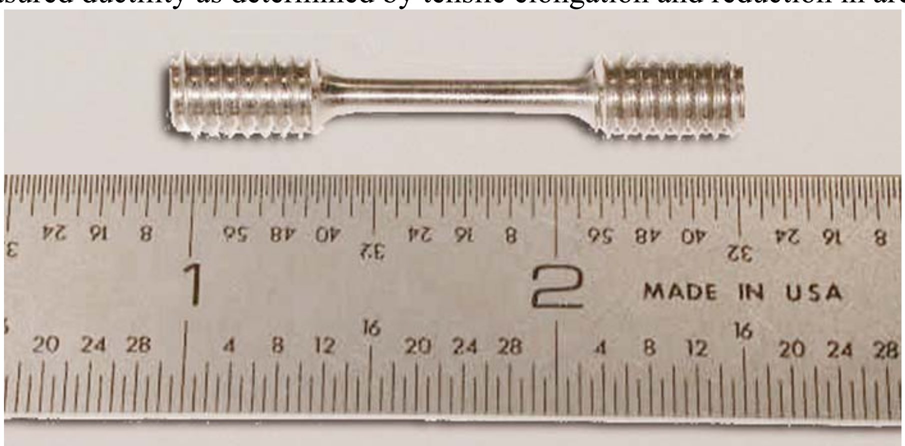

Figure 1. A tensile bar machined from a LENS repeatability tower sample. The bar has a 0.62" gage length and a 0.125" gage diameter.

Table 1. Values of Strength and Ductility for 304L Stainless Steel as Required by the Specification

Property	Specification Requirement
Ultimate Tensile Strength	75 KSI
Tensile Yield Strength	30 KSI
Ductility – Tensile Elongation	40%
Ductility – Reduction in Area	50%

Figures 2 and 3 show the LENS deposited material to have exceeded the strength requirements of the specification and show the strength measurements to have a low standard deviation among the samples (4 KSI and 6 KSI respectively). This result was encouraging and confirmed past studies that showed LENS deposited material to have superior strength properties to annealed material. Figures 4 and 5, however, show that a number of the LENS samples did not meet the ductility requirements. The tensile elongation measurements reported in Figure 4 still maintain an average value in excess of the requirement, but the standard deviation of the samples has increased to 12% ET. The process seems to have encountered problems on the 3rd and 5th days of sample deposition. The ductility as measured by reduction in area (Figure 5) paints an even gloomier picture with the average value dropping below the specification requirement and the standard deviation staying at 12% RA. Here, not only do days 3 and 5 have low values, but day 1 has dropped below the requirement line as well. The data shows that there is a repeatability problem, and the fracture surfaces must be studied to show the cause.

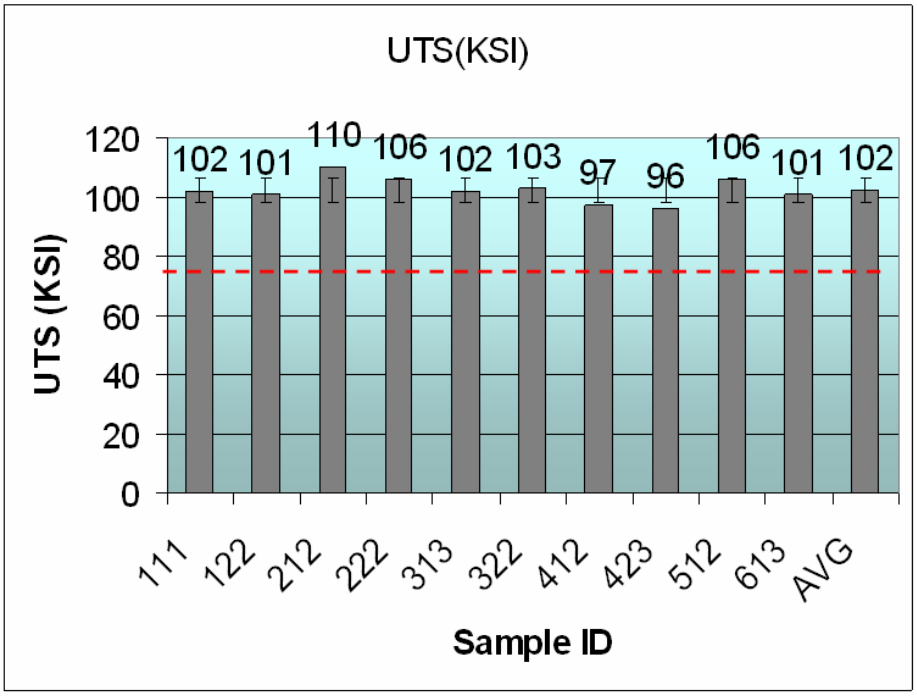

Figure 2. The Ultimate Tensile Strength for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required UTS for Annealed 304L as Found in the Specification

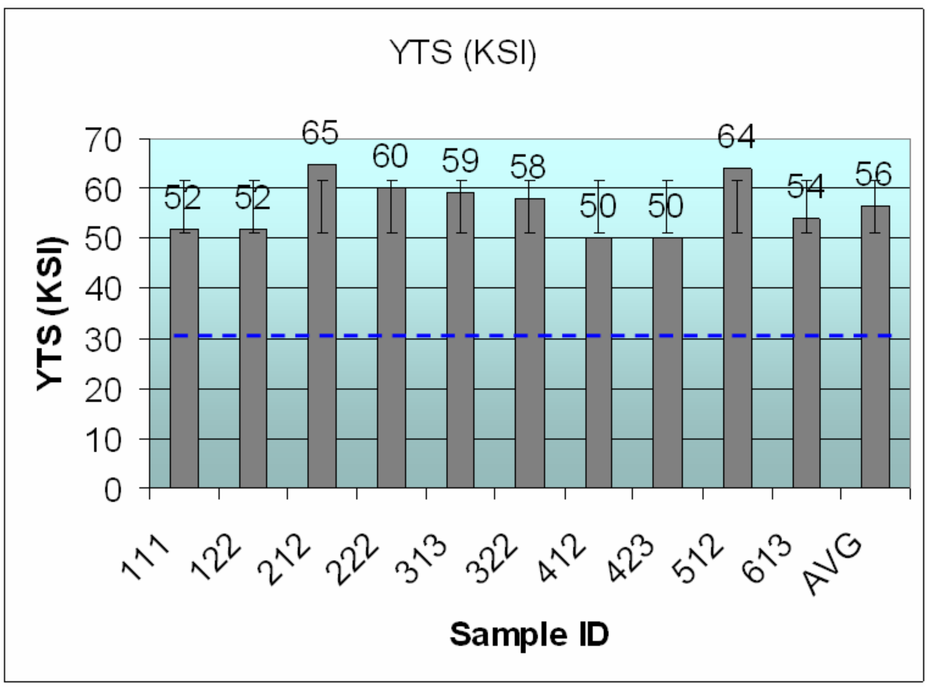

Figure 3. The Tensile Yield Strength for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required YTS for Annealed 304L As Found in the Specification.

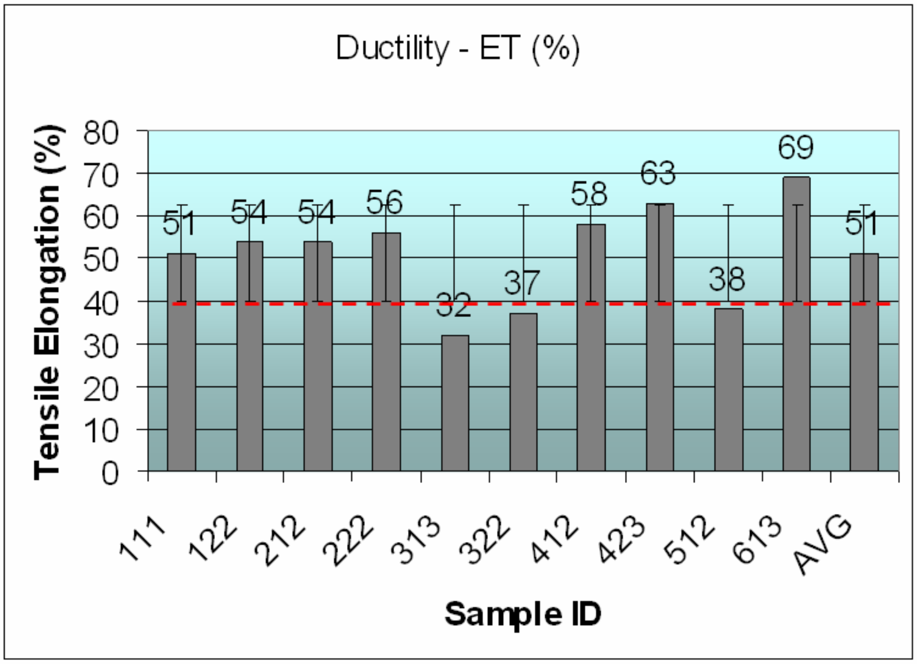

Figure 4. The Ductility as Measured by Tensile Elongation for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required ET for Annealed 304L as Found in the Specification

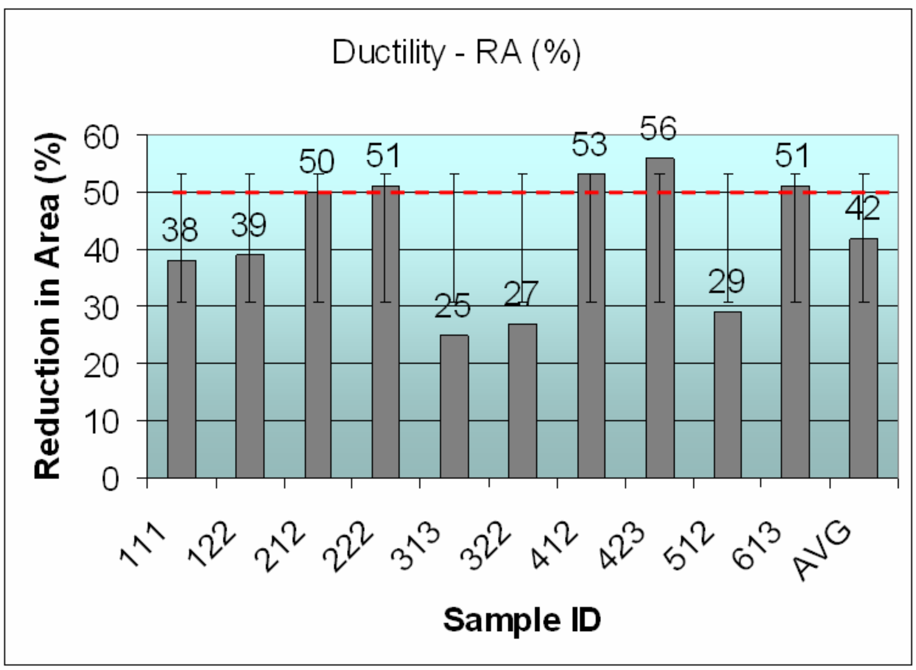

Figure 5. The Ductility as Measured by Reduction in Area for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required RA for Annealed 304L As Found in the Specification.

Fracture Surface Analysis

The fracture surfaces for 4 samples with ductility in excess of the specification value and 3 samples with ductility below the specification value are shown in Figure 6. The samples with good ductility show excellent cup-cone fracture surfaces with little porosity and no unmelted particles. The samples with low ductility show significant porosity, some unmelted particles, and, if there is cup cone fracture at all, it is offset to one side. The samples with poor ductility appear to have had process changes causing poor material characteristics. An analysis of the microstructure is necessary to add understanding to the poor ductility of some of the samples.

The top portion of each of the 10 samples was sectioned, potted, polished, and etched to show the microstructure. These images are shown if Figure 7 with the high ductility samples on the left and the low ductility samples on the right.

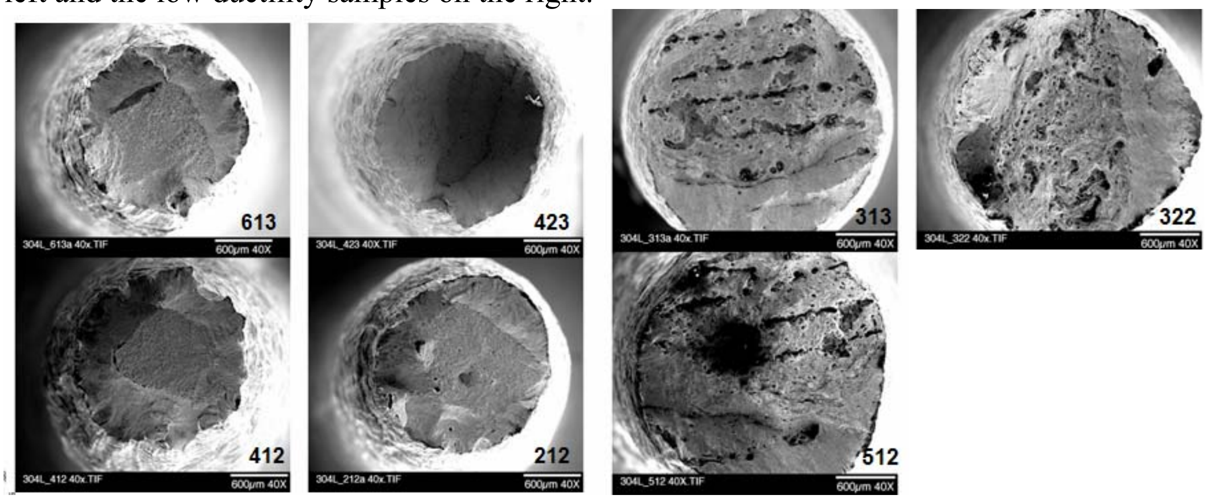

Figure 6. The Failure Surfaces of 4 Samples with Ductility in Excess of the Specification Value (left) and 3 Samples with Ductility Below the Specification Value (right) Show the Differences in Fracture Initiation.

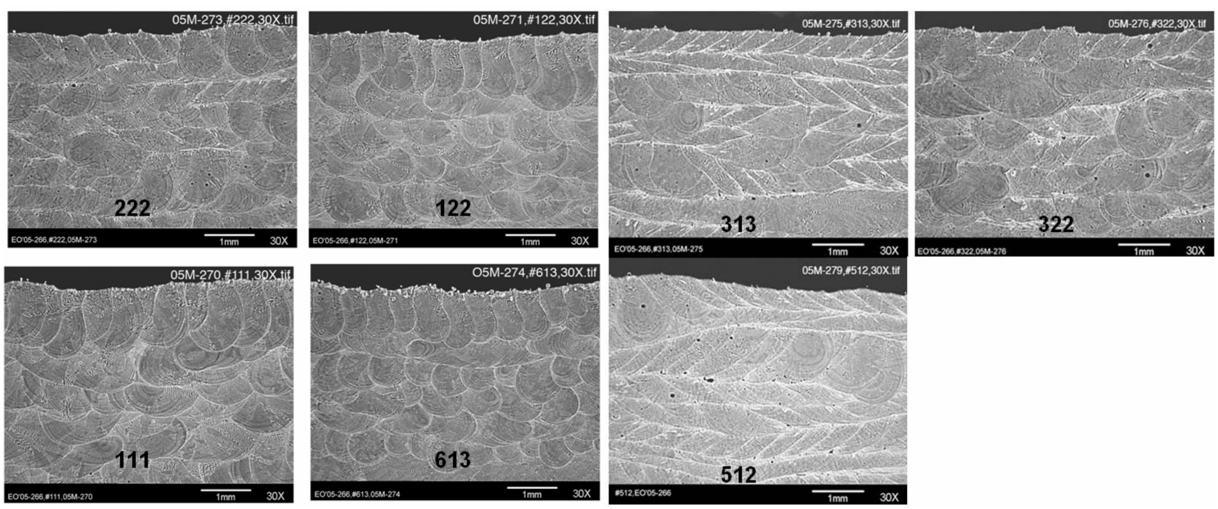

Figure 7. Micrographs of Polished 304L Samples. The 4 Samples on the Left Exhibited Ductility Above the Specification Value While The 3 Samples on the Right Exhibited Ductility Below the Specification Value.

The high ductility samples in Figure 7 show fairly even layers with only small amounts of melt pool variation. There is little porosity in these samples. The low ductility samples show wildly varying layer thickness with some huge melt pools. The low angle of the diagonal lines shows that the melt pool was very wide and that only a small portion of that original melt pool is being seen, the remainder having been remixed with later passes. In addition to the melt pool variations, there is significantly more porosity in these samples.

To determine a cause for the melt pool variation that resulted in the low ductility measured in the tensile testing, the LENS Log was queried to see if the operators had noted any problems with the build process. It was found that on all of the low ductility builds, there had been weld pool control problems noted by the operators. The source of the variation had been sought extensively, but no solution had been found at that time. The result of the problem caused the operators to see the closed-loop melt pool controller drive the laser power to its upper limit for some or all of a layer and then to regain control at a later time. Further investigation after the sample deposits showed that two wires were loose in the electrical control cabinet that caused an intermittent loss of control for the closed-loop melt pool controller. The problem was corrected and appears to have solved the control issues. The authors intend to perform another repeatability test to determine if the machine is in better control than found previously.

Conclusions

A repeatability test of the LENS process was conducted at Sandia National Laboratories. Thirty samples were deposited over the course of 12 weeks. Ten of the samples were randomly selected and machined for both metallographic analysis and for tensile testing. The tensile testing provided measurements of strength and ductility while the metallographic analysis gave a picture of layer morphology for the parts. The tensile testing has shown that the LENS deposited test samples showed higher strength than is required of annealed materials as defined in the relevant specification. The strength values also had a fairly small standard deviation. The ductility measurements showed significantly more variation with some specific samples falling below the required level. The average ductility as measured by % elongation still maintained an average value above that required by the specification, but the ductility as measured by %reduction in area had an average value below the specification.

Analysis of fracture surfaces revealed that the samples with ductility above the requirement had ductile cup-cone fracture surfaces with very little porosity and no unmelted powder. The samples with below-average ductility had large amounts of porosity, some unmelted powder particles, and did not exhibit cup cone fracture. The sectioned and polished surfaces showed the samples with above average ductility to have nice even layer thicknesses and regularly sized hatch lines while the below average samples had wildly varying layer thickness and evidence of a very large melt pool. The LENS Log revealed that the operators had recorded anomalies during the below average ductility builds in which the laser power would be driven to its highest value by the closed loop melt pool area controller. Though the cause was investigated during the test, it was not until after the test that the root cause was determined. Two control wires had become loose in the electrical cabinet causing the melt pool signal to intermittently have contact with the laser. So, while the results of the study showed a lack of repeatability of the LENS process, there was an assignable cause that has been corrected. It is hoped that a new study will be completed in the near future to quantify the system repeatability without the control issue.

Acknowledgements

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