SANDIA REPORT
SAND2006-6431
Unlimited Release
Printed November 2006

Process Qualification and Testing of LENS® Deposited AY1E0125 D-Bottle Brackets

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Abstract

The LENS Qualification team had the goal of performing a process qualification for the Laser Engineered Net Shaping™(LENS®) process. Process Qualification requires that a part be selected for process demonstration. The AY1E0125 D-Bottle Bracket from the W80-3 was selected for this work. The repeatability of the LENS process was baselined to determine process parameters. Six D-Bottle brackets were deposited using LENS, machined to final dimensions, and tested in comparison to conventionally processed brackets. The tests, taken from ES1E0003, included a mass analysis and structural dynamic testing including free-free and assembly-level modal tests, and Haversine shock tests. The LENS brackets performed with very similar characteristics to the conventionally processed brackets. Based on the results of the testing, it was concluded that the performance of the brackets made them eligible for parallel path testing in subsystem level tests. The testing results and process rigor qualified the LENS process as detailed in EER200638525A.

ACKNOWLEDGMENTS

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

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

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1. INTRODUCTION

The Laser Engineered Net Shaping ™ (LENS®) process utilizes a laser, powdered metal, and a computer solid model to fabricate fully dense and fully functional metal components. The LENS Qualification Technology Investment project team, sponsored by NNSA's Office of Stockpile Technology (NA123), set out to gain process qualification for the LENS process. This qualification was performed on the AY1E0125 D-Bottle Bracket. The steps of the process included process development and materials analysis, LENS depositing of near net shape brackets, finish machining the LENS deposited brackets, and equivalency testing of the brackets in weapons environments specified by Environment Specification ES1E0003. The purpose of the testing was to evaluate the equivalency of the LENS produced brackets with conventionally machined brackets. Upon proving equivalency, the brackets would be allowed to participate in parallel path, subsystem-level testing with the conventionally produced brackets. Completion of this process, along with process qualification, would give product engineers and other potential LENS users the needed confidence to specify LENS as the primary path process for fabrication, repair, or modification of their components.

1.1. Purpose

The purpose of this document is to record the development, fabrication, and testing steps taken in the Qualification of the LENS process for producing the AY1E0125 D-Bottle Bracket. This record will help future LENS users to optimize the LENS process for their component more quickly. The document also serves to record both the development process and the capabilities of LENS so that future product designers will have increased confidence in the LENS process.

1.2. Scope

This document includes the activities completed by the LENS Qualification team to fabricate and test LENS deposited D-Bottle brackets. Included are analyses of the LENS deposited material, results of repeatability testing of the LENS process, fabrication history for the LENS brackets including lessons learned on alternative fabrication methods, finish machining methodology, and testing methods and results for the LENS brackets. The process qualification is not specifically included here as it is detailed in EER200638525A. This document concludes with the D-bottle bracket product engineer's analysis of the testing results.

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2. THE MECHANICAL PROPERTIES OF LENS DEPOSITED 304L STAINLESS STEEL

2.1. Repeatability Testing of LENS Parts

Qualification requires an analysis to be made of the process repeatability and control. In an effort to assess this repeatability and to assure product engineers of the capability of the LENS process, a repeatability test was performed.

2.1.1. Depositing the Test Samples - Test Group 1

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”. A few of these samples are shown in Figure 1. 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 any 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.

Figure 1. A Subset of the Repeatability Samples Shown In the As-Deposited State

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, 621 would be the sixth day of depositing repeatability samples, the second set of the day, and the first 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.

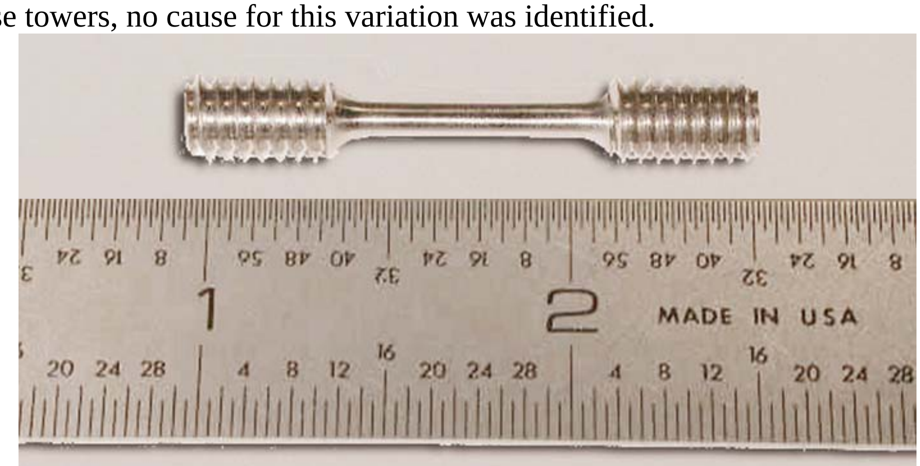

Figure 2. A Tensile Bar Machined from a LENS Repeatability Tower Sample. The Bar Has a 0.62" Gage Length and a 0.125" Gage Diameter.

2.1.2. Sample Testing – Test Group 1

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 plane was 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. A machined LENS tensile bar is shown in

Figure 2. Values were recorded for ultimate and tensile strengths as well as ductility measured by reduction in area and tensile elongation.

2.1.3. Tensile Testing Results – Test Group 1

The uniaxial 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 induced 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. Figure 3 and Figure 4 show the measured ultimate tensile strength and tensile yield strength. Figure 5 and Figure 6 show the measured ductility as determined by tensile elongation and reduction in area.

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%

Figure 3 and Figure 4 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. Figure 5 and Figure 6, however, show that a number of the LENS samples did not meet the ductility requirements. The tensile elongation measurements reported in Figure 5 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 6) 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. The data is presented in tabular form in Table 2

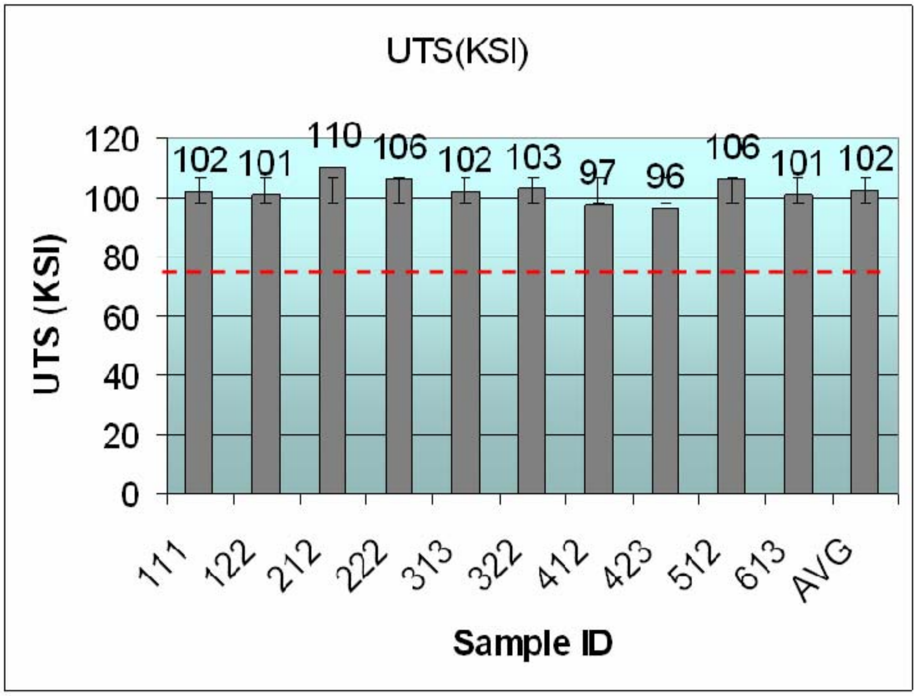

Figure 3. The Ultimate Tensile Strength for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required UTS for Annealed 304L as Found in the Specification

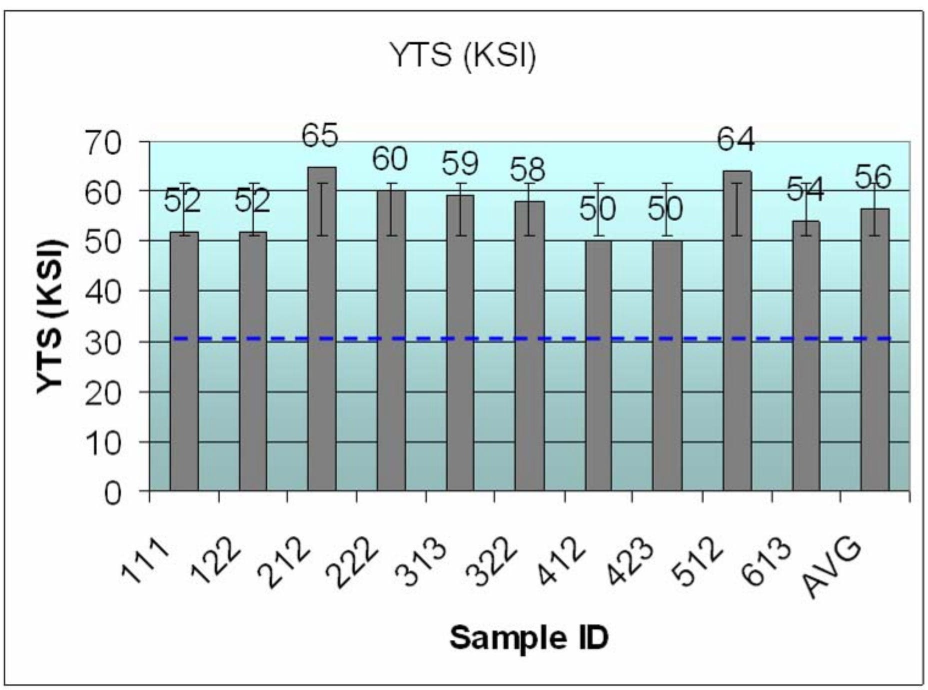

Figure 4. The Tensile Yield Strength for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required YTS for Annealed 304L As Found in the Specification.

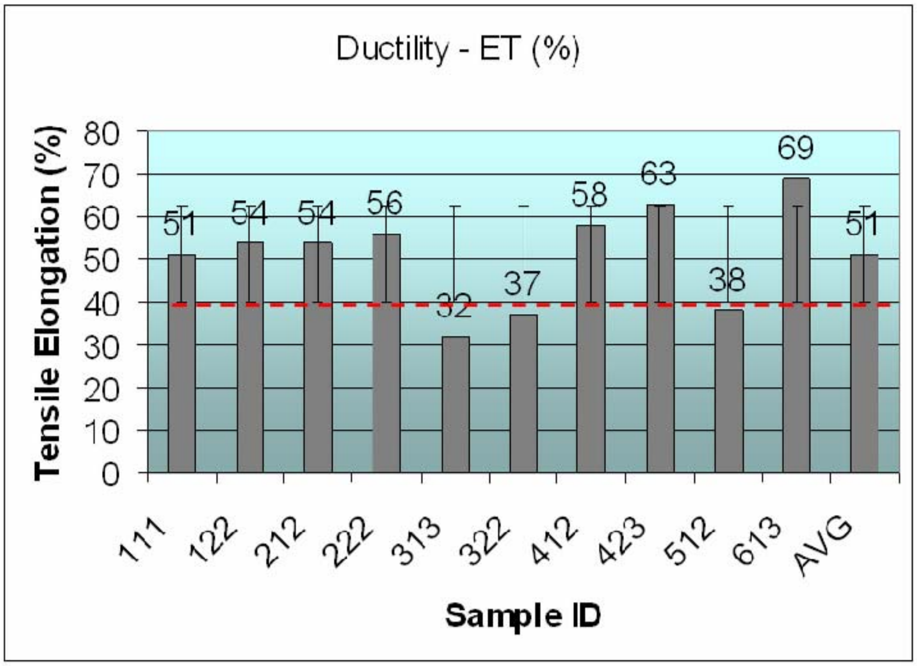

Figure 5. The Ductility as Measured by Tensile Elongation for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required ET for Annealed 304L as Found in the Specification

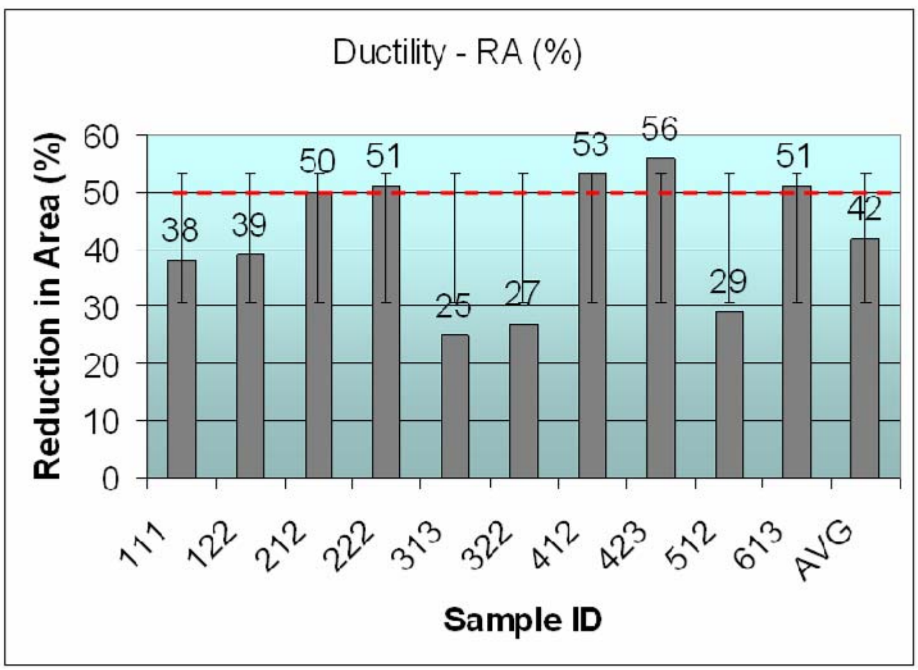

Figure 6. The Ductility as Measured by Reduction in Area for the 10 LENS deposited Samples as Determined by Tensile Testing. The Dotted Line Represents the Required RA for Annealed 304L As Found in the Specification.

Table 2. 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

Table 2 lists the tensile properties of the first group of coupons produced to demonstrate the repeatability of the process. Figure 3.1 shows the average properties and their variation. The specification for 304L, ASTM A240, calls for a minimums in ultimate tensile strength of 70 KSI, yield tensile strength of 25KSI, and total elongation 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 as few cases the elongation 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.

2.1.4. Fracture Surface Analysis – Test Group 1

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 7. 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 8 with the high ductility samples on the left and the low ductility samples on the right.

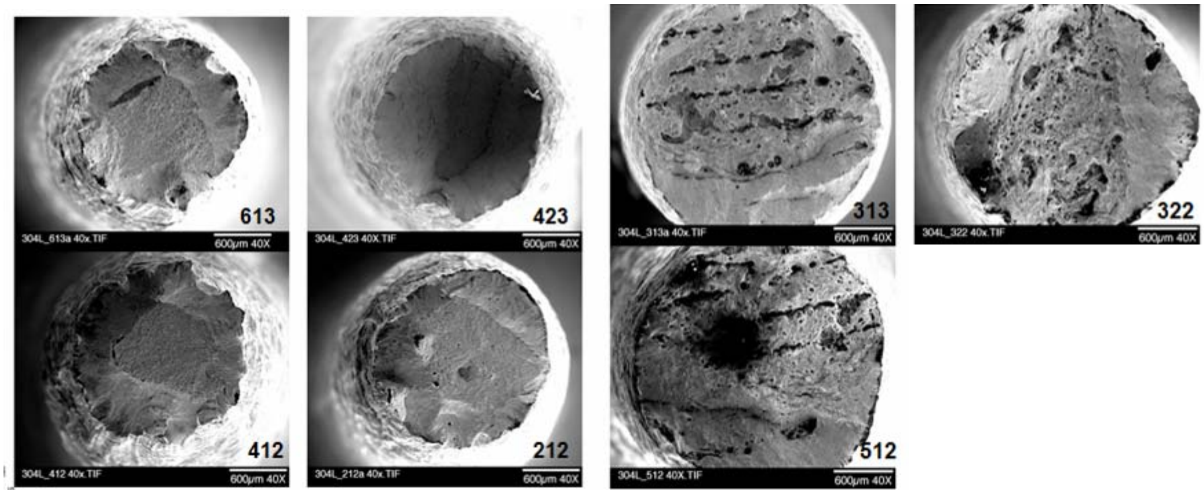

Figure 7. The Failure Surfaces of 4 Samples with Ductility in Excess of the Specification Value (left) and 3 Samples with Ductility Below the Specification Value (right) Show the Differences in Fracture Initiation.

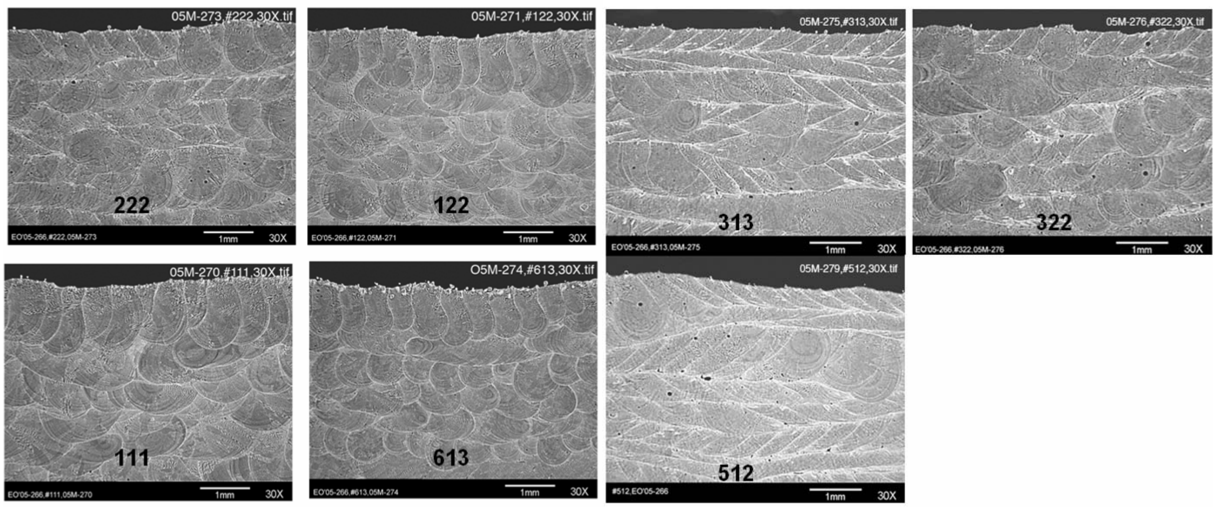

Figure 8. Micrographs of Polished 304L Samples. The 4 Samples on the Left Exhibited Ductility Above the Specification Value While The 3 Samples on the Right Exhibited Ductility Below the Specification Value.

The high ductility samples in Figure 8 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.

2.1.5. Conclusions from Repeatability Testing – Test Group 1

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.

2.1.6. LENS Depositing - Test Group 2

Because of the variability seen in the first repeatability testing, a second similar test was performed to determine whether the sources of variability had been addressed. In this similar test, 3/8”X3/8”X2” towers of 304L stainless steel were deposited in groups of 3. A total of 30 samples were deposited with 9 on the first day, 6 on the second day, 6 on the third day, and 9 on the fourth and final day. The towers are shown in Figure 9. Again, a random selection of towers was made and these towers were separated from the substrates. The samples were machined into tensile specimen as before and tested for ultimate and yield strengths as well as ductility determined by percent elongation and reduction in area. A smaller sample was selected for metallography due to time constraints and the confidence that tensile test results would show high repeatability of mechanical properties, thus eliminating the need for extensive metallography. Unfortunately, time did not permit the analysis of this sample group.

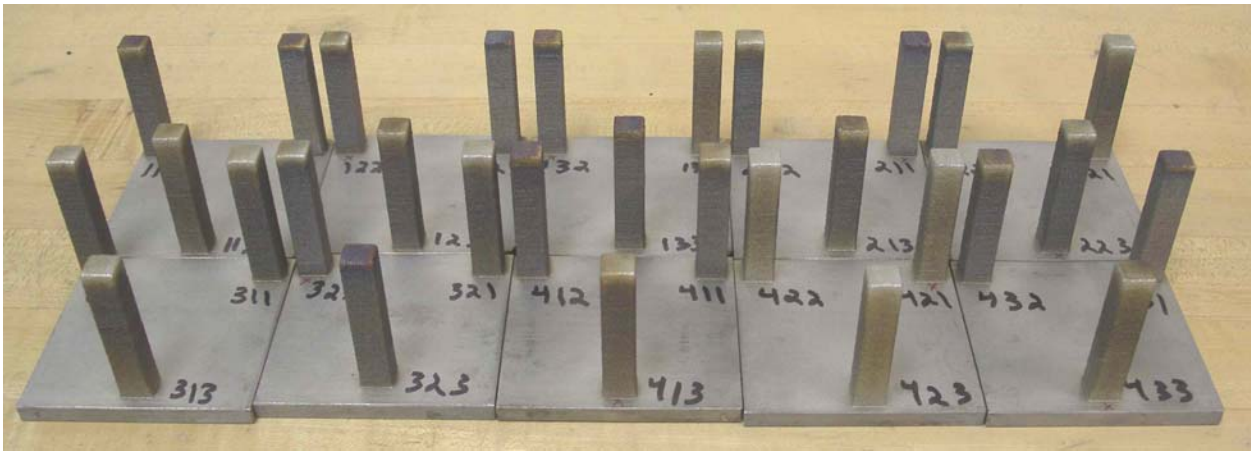

Figure 9. Repeatabiliity Sample Group 2 Showing All Towers in the As Deposite State

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3. LENS PROCESS DEVELOPMENT AND FINISH MACHINING FOR 304L D-BOTTLE BRACKETS

Once the process development has been completed and the material characteristics and properties are well understood, the process must be used to make parts. Because LENS is a near net shape process, it is also necessary to develop a finish machining process to complete the parts. Over the course of this effort, several methods were investigated for making D-Bottle Brackets. Important lessons were learned for both the depositing of these components and the finish machining activities required for part completion.

3.1. Depositing of Hybrid LENS Brackets

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 approach, the bracket features would be deposited onto the plate structure which would minimize the time required to deposit and finish machine the parts.

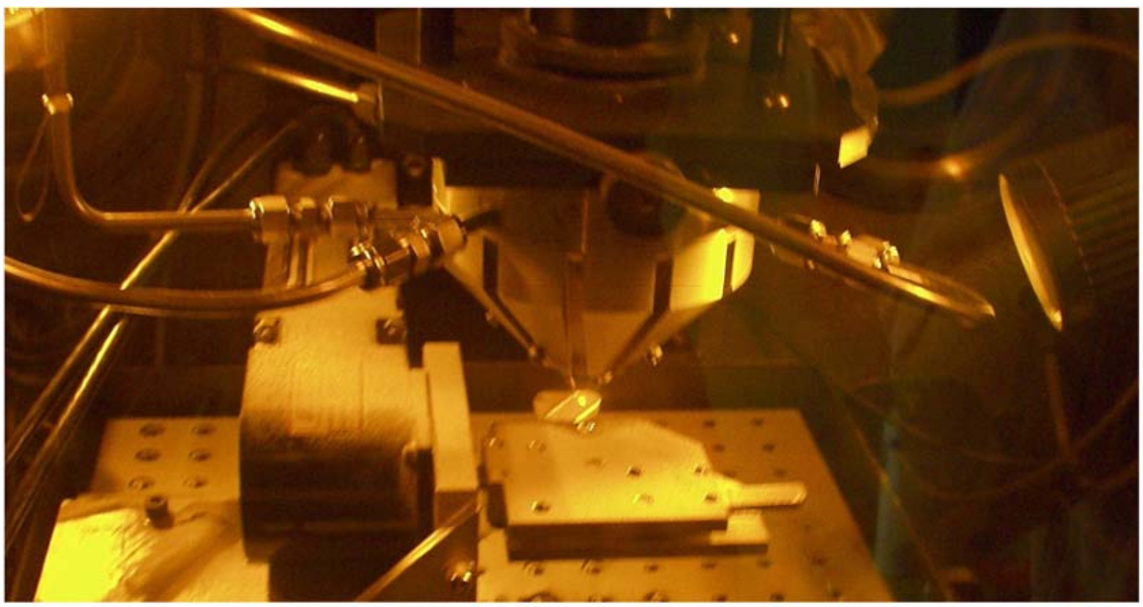


Figure 10. Initial Attempts at creating a Hybrid Bracket Utilized a Precut L-Bracket Plate as the Substrate Which Was Included in the Final Part

The L-bracket was fixtured in a sandwich fixture as shown in Figure 10 and as shown in Figure 11 as Method A, and was mounted on a rotary fixture. This allowed the LENS process to put features on all sides of the part. Unfortunately, this method induced considerable levels of stress in the part and the brackets deformed badly. Many different approaches were attempted including depositing a layer on one side of the bracket and then flipping the bracket to deposit on the other side. It was found that the bracket deformed when the first layer was deposited and following with a layer immediately deposited on the other side was not able to eliminate the induced deformation. Another attempt included preheating one side with the laser, flipping the bracket over and preheating the other side, and then depositing on one of the two sides. In the end, it was concluded that the localized heating of Method A was too significant to overcome without having additional pathways for heat conduction. A bracket created by Method A is shown in Figure 12.

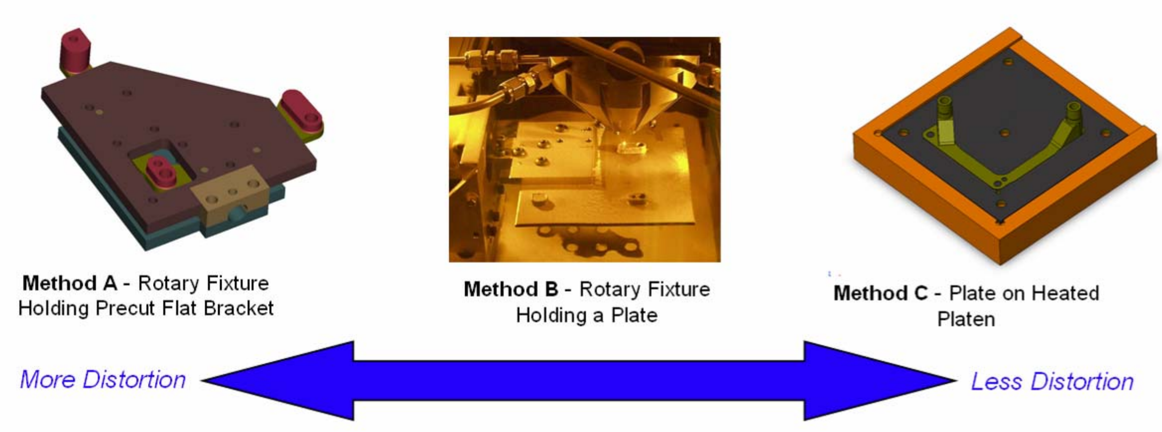


Figure 11. Three Methods of Creating Hybrid Brackets

The team next attempted Method B (Figure 11) in which the features were deposited on a plate instead of on a precut L-bracket. The concept was that this plate would provide additional heat conduction pathways and would be cut or milled to the shape of the bracket after the deposition process. Again, the bracket was positioned in a pancake fixture and mounted on the rotary axis to give access to each side of the part. Though there was significantly less deflection using this method, the deflection was still unacceptable. A bracket created by Method B is shown in Figure 12. An indication of the amount of deflection can be seen as the yellow bump just below the letter “B” which is the deflection from the boss feature on the other side (as seen on the Method A bracket just below the letter “A”.)

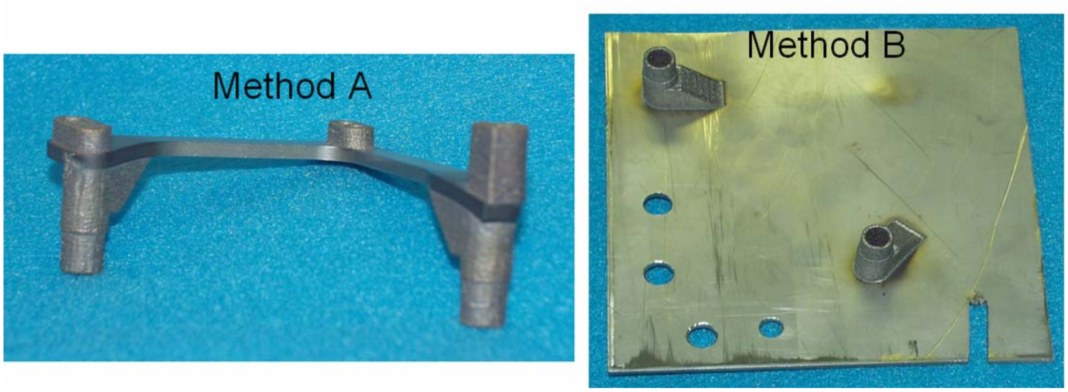
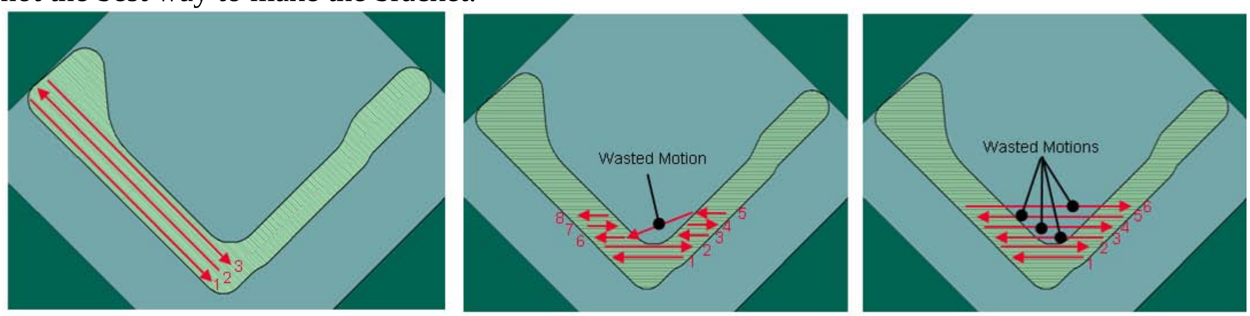


Figure 12. Brackets Created by Methods A and B

A strategy that has been shown to work well in other efforts is the use of a hot plate to preheat the substrate significantly and thus to reduce any temperature differential between the deposition region and other areas of the part. This strategy, here referred to as method C, utilizes the same thin plates used in method B, but the substrate plate is positioned in a large block fixture (to maximize contact area) and mounted on a hot plate as shown in Figure 11c. This method produced distinctly less distortion than either of the other methods. There was some concern about the potential effects that the hot plate might have had on the part’s microstructure by preventing the rapid melt pool solidification that gives LENS its enhanced strengths and ductility, but time did not permit metallurgical analysis.

In addition to changing the substrate and fixturing methods, the heat input was carefully controlled by changing the process planning strategy. It is possible to control the planning characteristics and hatch direction of the automatic process planner as shown in Figure 13. Strategy C1 used scans aligned with the article being fabricated which minimizes deposition time, but increases the rate at which heat is induced in the part and leaves no time for the part to cool down. Strategy C2 builds along a section, but traverses in the shorter direction which gives short cool-down times when the laser shutter is closed at the end of each path. And strategy C3 makes one pass on one feature and then moves to the other feature for one pass. This strategy puts heat into the part at the slowest rate, but also builds the part at the slowest rate. Strategy C3 showed the smallest amount of heat deformation and the link between hatch orientation and geometry orientation was shown to have a significant effect on the part deformation. Even with these process improvements, it was ultimately decided that the hybrid methods were probably not the best way to make the bracket.



Method C1. Aligned Laser Path Causes Maximum Distortion But Has Shortest Build Time

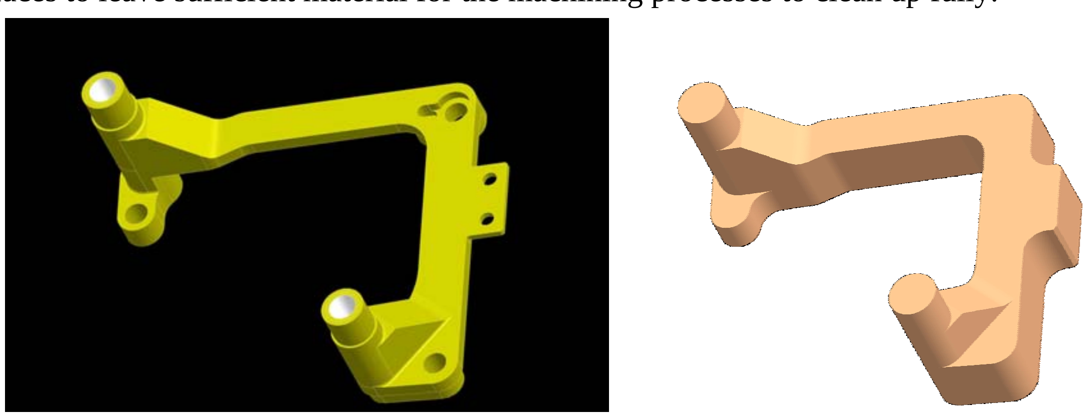
Method C2. 45° Hatch With SmartFill II Causes Less Distortion And Has Only Slightly Longer Build Time

Method C3. Direct 45° Hatch Causes Least Amount of Distortion But Has The Longest Build Time

Figure 13. Three Strategies for Controlling the Heat by Choosing the Hatch Direction Utilized in Method C

3.2. Depositing of Fully LENS Brackets

The next approach was to build the full bracket 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.



(A) (B)

Figure 14. Solid Models of Brackets in the Finished Condition (A) and as Modified for LENS Depositing with Support Structure, Offset Walls, and Filled Holes

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 surfaces offset by 0.020” as shown in the left image in Figure 15. The rough LENS 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 subsequent machining process. The substrate edges were not square and the substrate had distorted during the 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 shown in the right image in Figure 15.

Figure 15. LENS Deposited Brackets in Near Net Shape and Finish Machined Showing Some of the Lessons Learned

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 15. 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 of metal components.

The brackets are relatively large for LENS deposition and the process parameters were easily determined because of the very uniform heat conduction pathways through the part. The processing conditions are given in Table 3.

Table 3 . 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

3.3. Machining of Fully LENS Brackets

A second set of brackets was completed that had several process improvements. First, a new fixturing system was developed. This system had a fixturing subplate with labeled holes alternating between dowel holes for positioning and threaded holes for fastening. Two subplates were made so that the LENS machine and the finish machining center would both have matching plates on which to position the substrate and LENS part. The substrate is shown in Figure 16 and the assembly of the substrate on the subplate and onto the machine tool is shown in Figure 17.

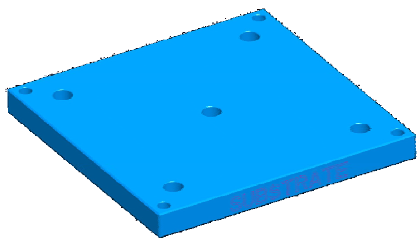


Figure 16. Model of Machined Substrate with 4 Dowel Holes for Locating and 5 Bolt Holes for Fastening

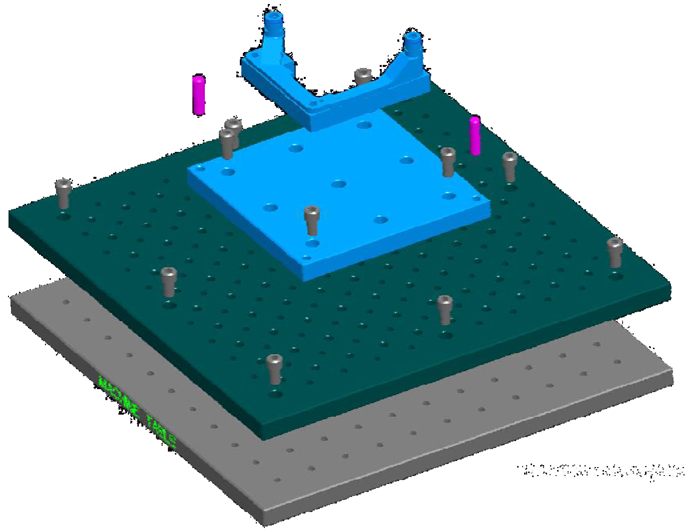


Figure 17. Assembly of LENS Substrate on Positioning Subplate and into Either the LENS Machine or the Finish Machining Center

This fixturing system also addressed one other significant concerns identified in the first round of depositing fully-LENS brackets. When the initial brackets were deposited, the substrates deformed some from the heat. This caused the substrate plate to be very difficult to install in the machining process because it could no longer be positioned flat against the subplate and could instead be positioned in a variety of angles as the part rocked on the now rounded substrate bottom. In the new fixturing system, round button locators or washers were positioned under the substrate and as close to the bolts as possible. These lifted the substrate slightly off of the subplate. If the heat caused any deformation in the substrate during the LENS process, the substrate now had room to deform but the part was still located with respect to the buttons or washers. The effect was that the part could be easily located in the machining center in exactly the same orientation as it had been in the LENS machine and there was no ambiguity as to what was level. A bracket created by LENS utilizing the lessons described is shown in Figure 18.

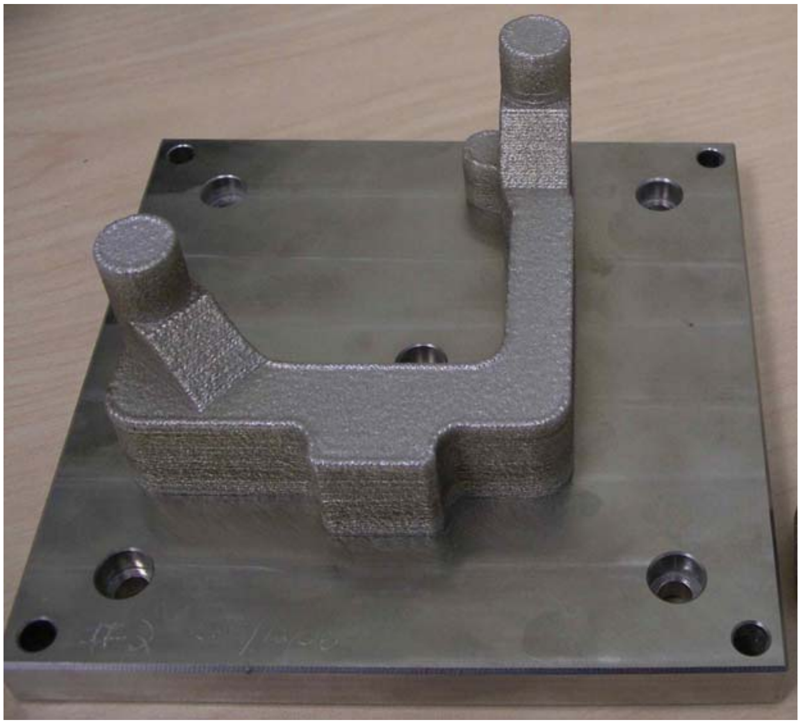


Figure 18. A LENS Deposited Bracket Shown on the New Substrate System Employing the Process Improvements Identified in the First Round of Bracket Deposition

The LENS deposited parts were machined by positioning the part and substrate on the fixturing subplate in the machining center. The part was initially skim cut back to the 0.020” offset that was used in the initial set of brackets, and then the top surfaces and features were machined on the part. A bracket is shown in this condition in Figure 19.

Once this top machining was completed, it was time to remove the bracket from the substrate so that the bottom features could be machined. A pocket was machined on the back side of the substrate that was larger than the bracket outline on the top side and the bracket was then removed from the substrate with a wire EDM. The pocketing exercise made the wire time much less since there was less material thickness to erode. The pocketing and removal steps are shown in Figure 20.

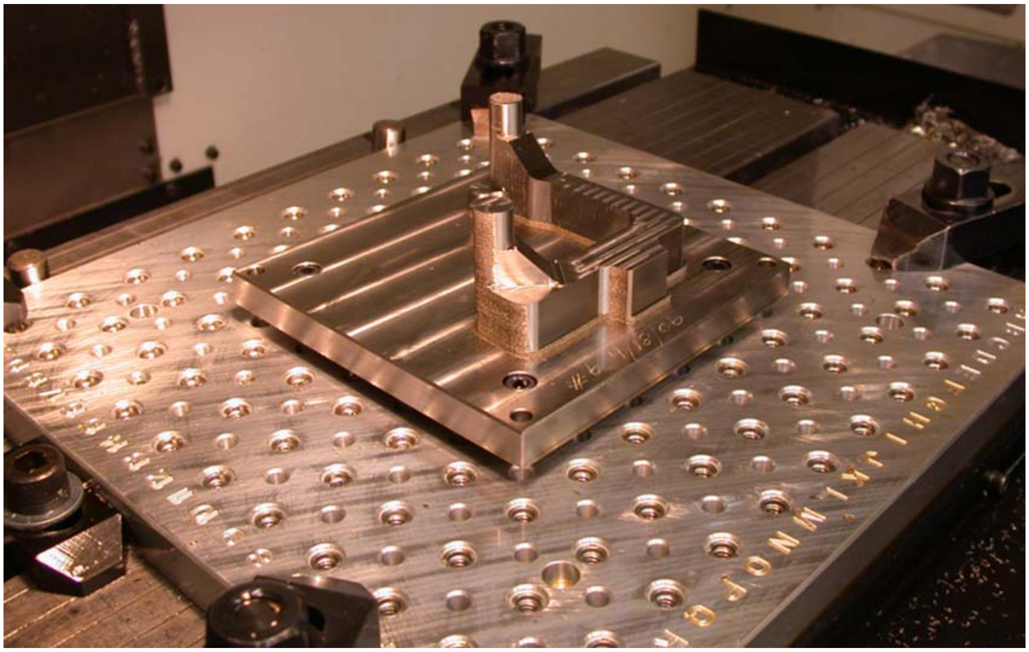


Figure 19. LENS Deposited Part During the Machining Process. The Fixture Plate and Machined Substrate Were Used in the LENS Machine As Well To Match Locating Positions. Note the Lack of Any Holes in the LENS Deposited Part.

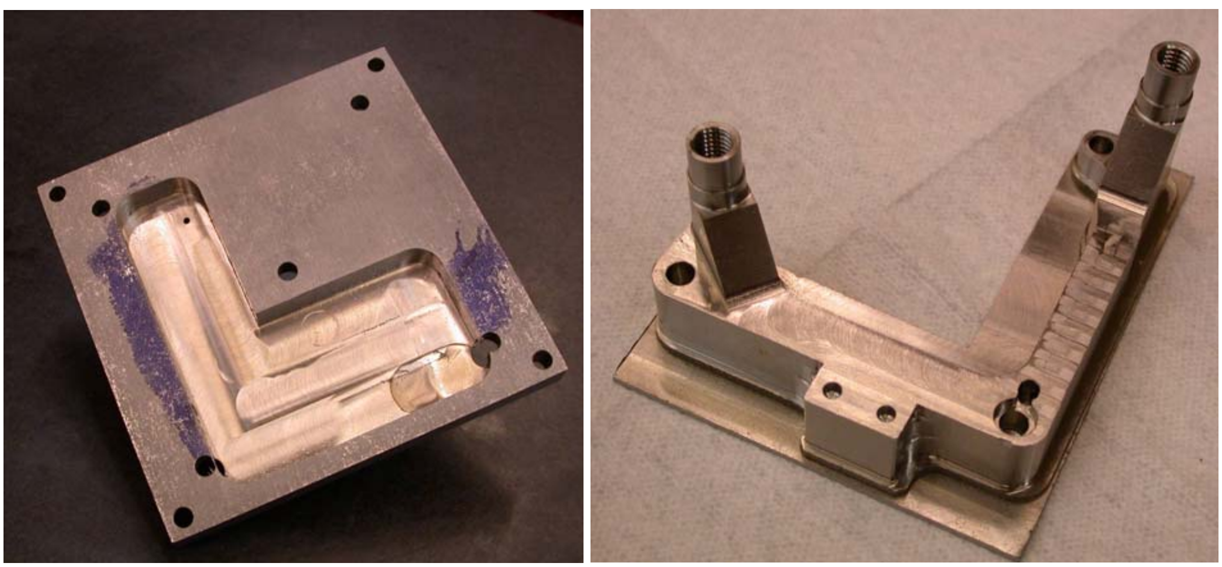


Figure 20. The Bottom Side of the Bracket Substrate is Pocketed (left) to Enhance Faster Removal of the Partially Machined Bracket from the Substrate (right)

Once removed from the substrate, the part was mounted upside down in a vise with conformal softjaw features and the bottom side of the part was finished machined. The softjaw fixture is shown in Figure 21 and the completed part is shown in Figure 22.

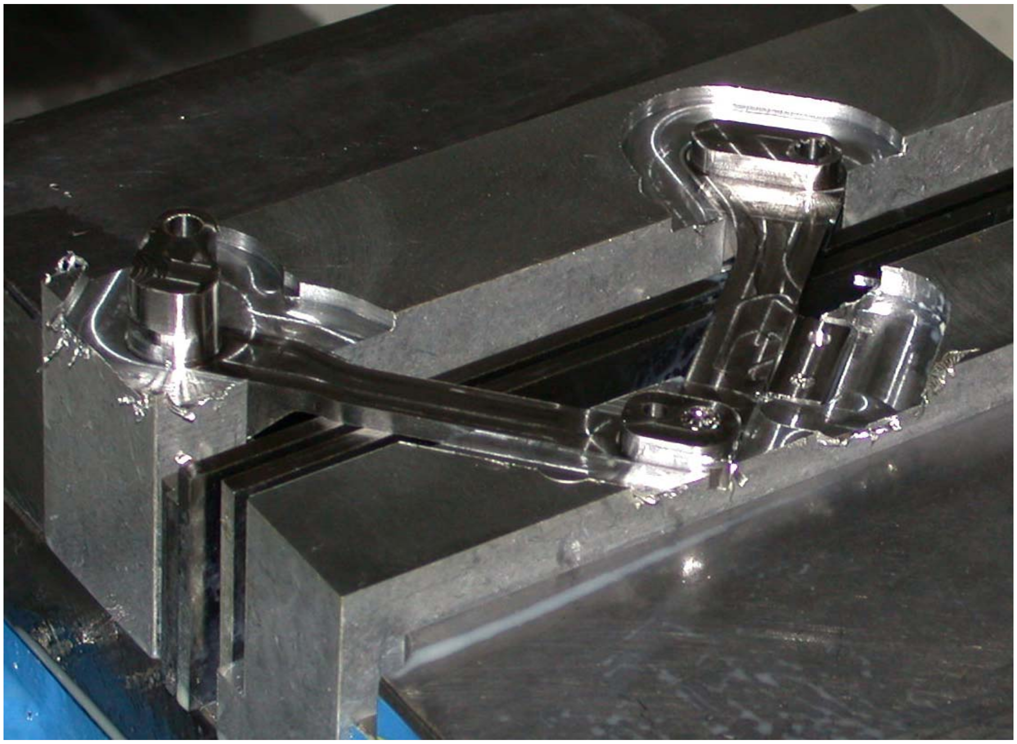


Figure 21. Bracket Shown in the Softjaw Fixture for Machining of the Bottom Side

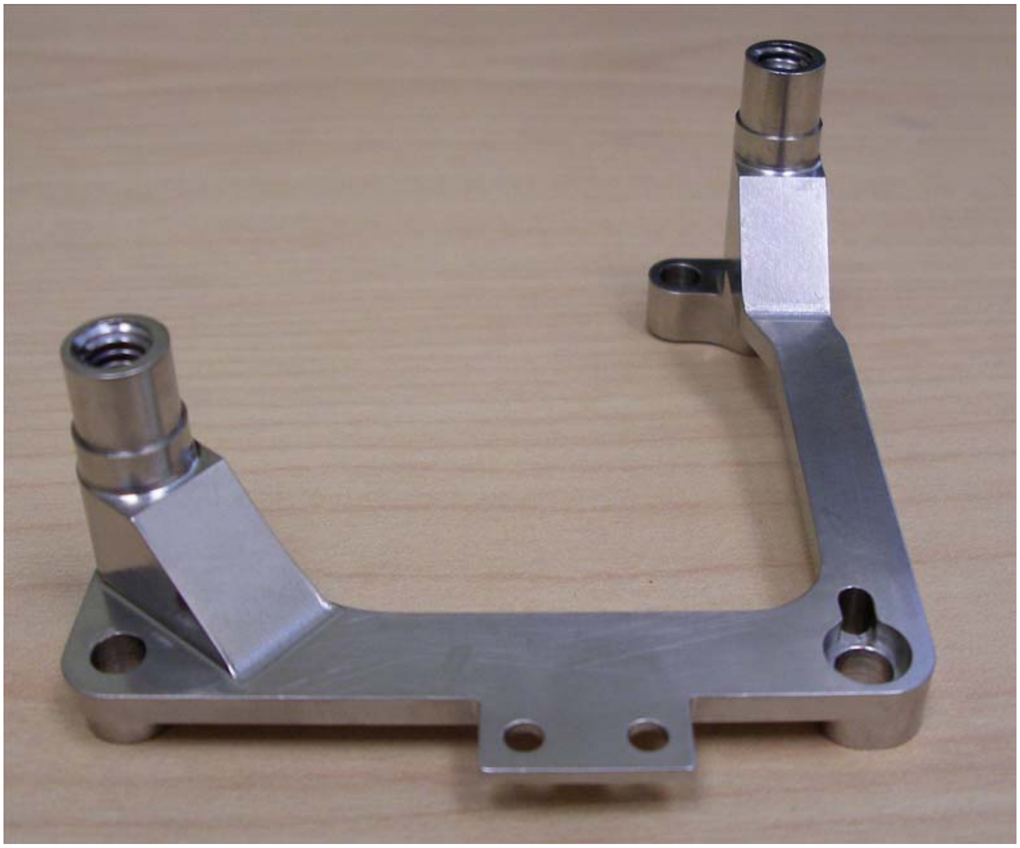


Figure 22. Completed Fully LENS Deposited Bracket After Finish Machining

4. PERFORMANCE AND EQUIVALENCY TESTING OF LENS DEPOSITED AND CONVENTIONALLY MACHINED BRACKETS

Once the brackets had been fabricated by LENS and finish machining processes, the brackets needed to be tested against conventionally produced brackets to compare the parts' performance. This testing included a mass analysis, modal testing in the component (free-free) and assembly (fixed-fixed) states, and assembly drop testing.

4.1. Mass Analysis

After the LENS deposited parts had been finished machined, their mass was measured to confirm part density and to help identify the source of any differences in the modal analysis (ping) testing. A total of 3 LENS deposited and 3 conventionally processed (CP) brackets were tested. The results are given in Table 4 and show that the LENS brackets were, on average, 0.008 lbs. heavier with a standard deviation of 0.0014 lbs. This weight difference was not significant or troublesome, especially given the low standard deviation which shows good process repeatability and control. In fact, the mass can easily be the product of finish machining more than the original LENS depositing. This may be the source of the difference as the LENS brackets were machined by a different process than the CP brackets. One positive aspect was that the mass analysis showed the LENS deposited brackets to be fully dense, which is often a concern of those who are just being introduced to the LENS process.

Table 4 . Brackets Testing Matrix Showing Mass, Which Brackets Were Tested for Dynamic Response, and Method By Which Each Was Created

Part ID	Wt (lbs) (914)	Wt (lbs) (955)	Ping Test Status	Drop Test Status	Comments
29	0.2465	0.245	X	X	Conventionally Processed
27*		0.245	X	X	Conventionally Processed
26*		0.245	X	X	Conventionally Processed
4C	0.2552	0.255	X	X	LENS
7D	0.2529	0.250	X	X	LENS
5E	0.2534		X	X	LENS
AVG	0.2543				0.008 heavier
STD DEV	0.0014				
PCT DEV	0.54				

4.2. Dynamic Response

In addition to the mass analysis, it is important to measure the structural dynamic response of the brackets. This response is measured through modal analysis and drop testing. The modal analysis is measured in both the component (free-free) condition and in the assembly (fixed-fixed) condition.

4.2.1. Free-Free Modal Analysis

In the free-free modal (ping) test, the parts were suspended in a free-free state and an instrumented hammer was used to strike the part. Accelerometer bonded to the part were used to determine the free-state modal frequencies. Figure 23 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, both acceptable ranges. 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.

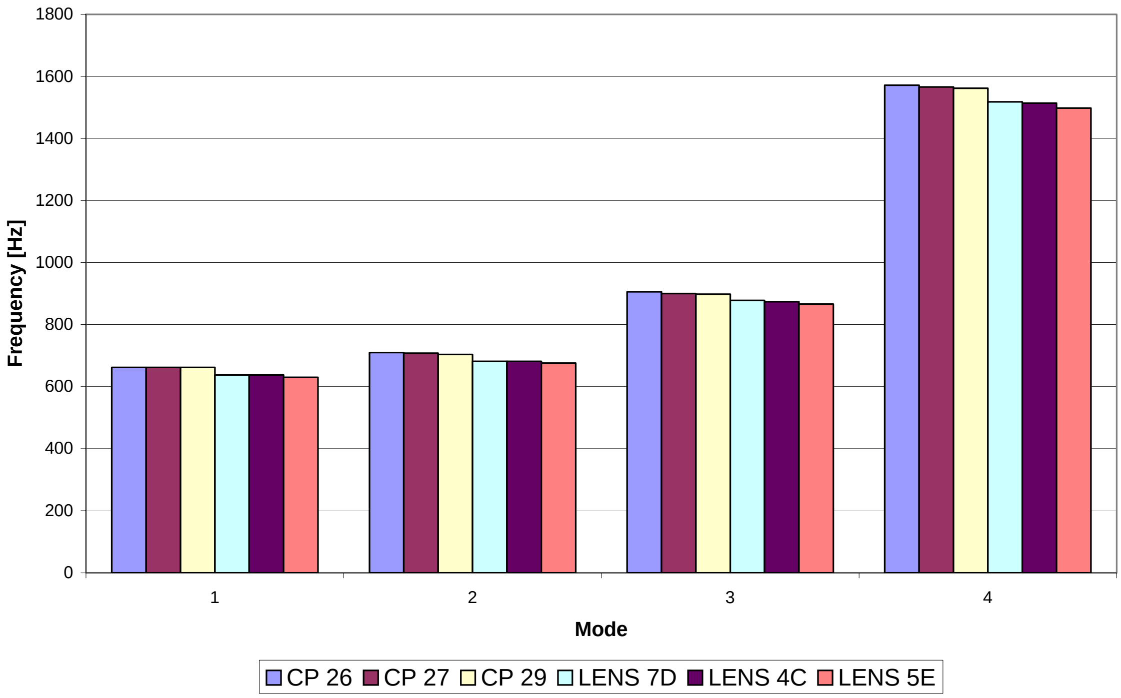


Figure 23. Free-Free Modal Comparison of LENS and Conventionally Processed (CP) Brackets Showing Very Similar Dynamic Behavior and Good Repeatability for the First Four Modes

4.2.2. Assembled Modal Analysis

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 24, 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.

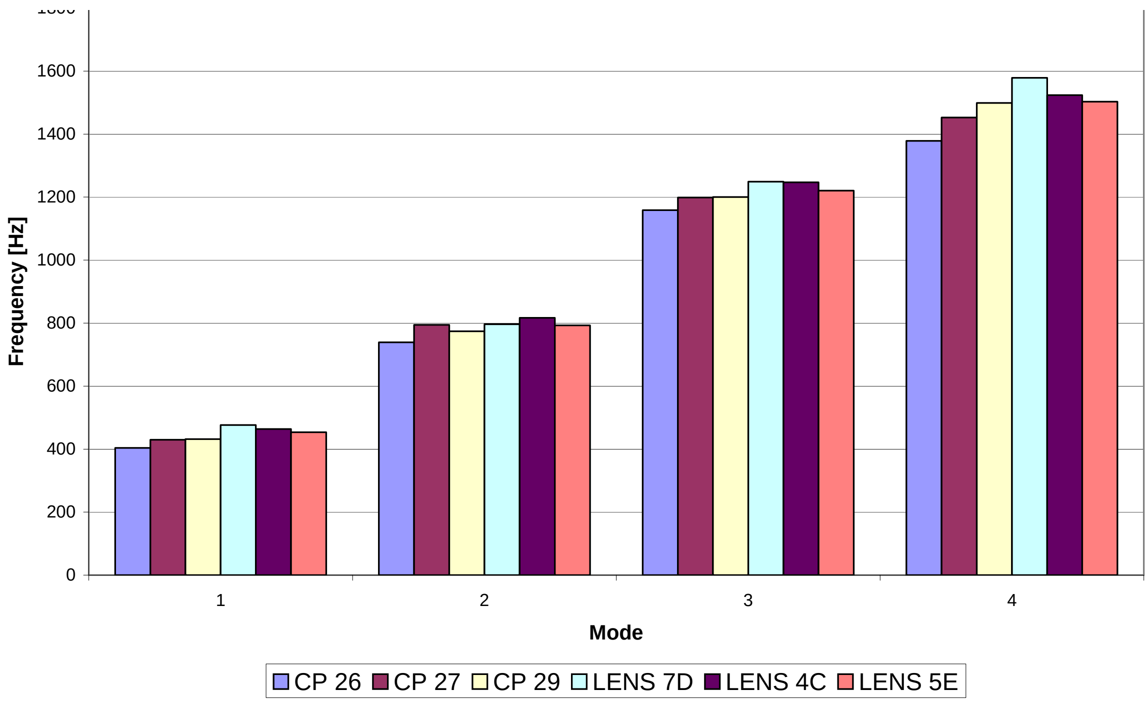


Figure 24. Modal Comparison of Subsystem Assembly Containing Conventionally Processed (CP) and LENS Brackets

4.2.3. Haversine Shock Testing

The final test of the brackets' structural dynamics was the drop test. The subsystem assemblies containing LENS and CP parts were subjected to a Haversine Shock as shown in Figure 25. 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 the on-axis (Figure 28) and cross-axial (Figure 26 and Figure 27) directions. The peak on-axis accelerations were all within 2% of one another. It is likely that much of the small differences seen in test results were caused by assembly contact stiffness differences.

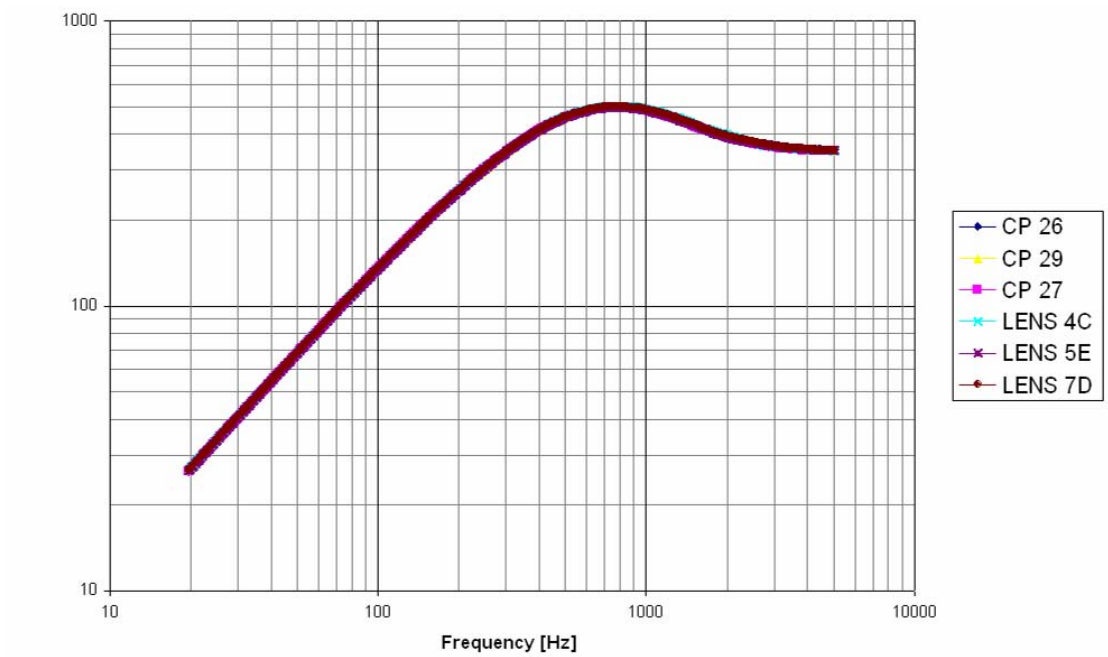


Figure 25 . Haversine Shock Input as Measured in Each Assemblies Containing CP or LENS Processed Brackets

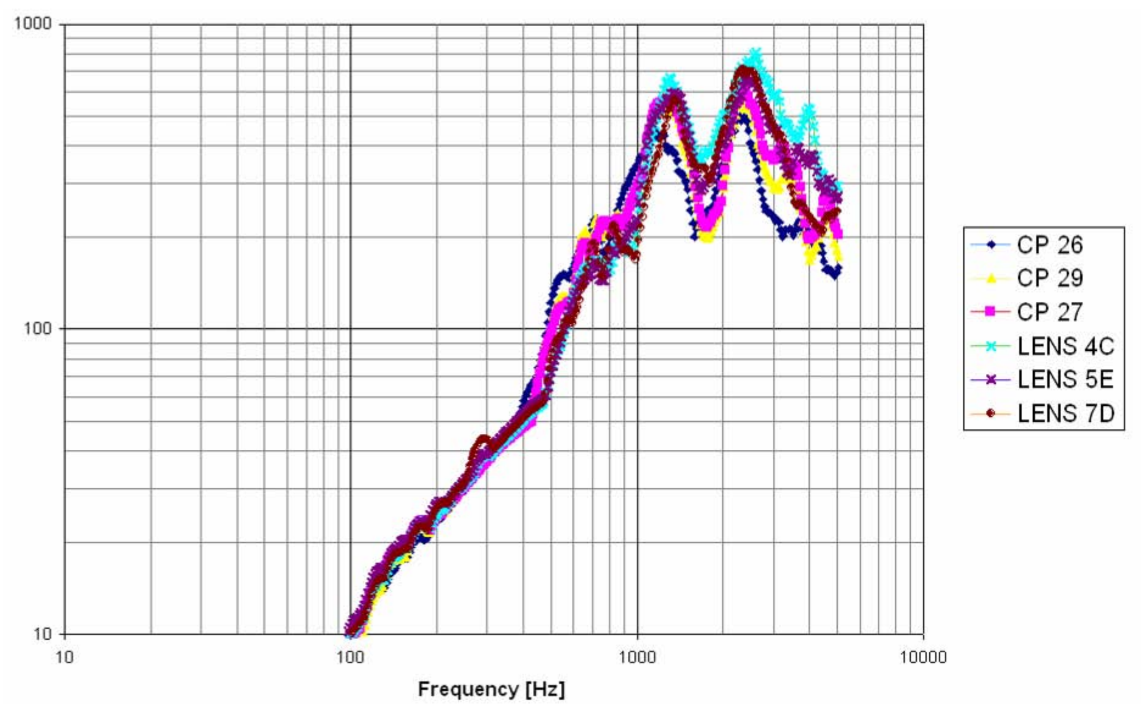


Figure 26. Shock Response Spectra as Measured in the Cross Axis X Direction

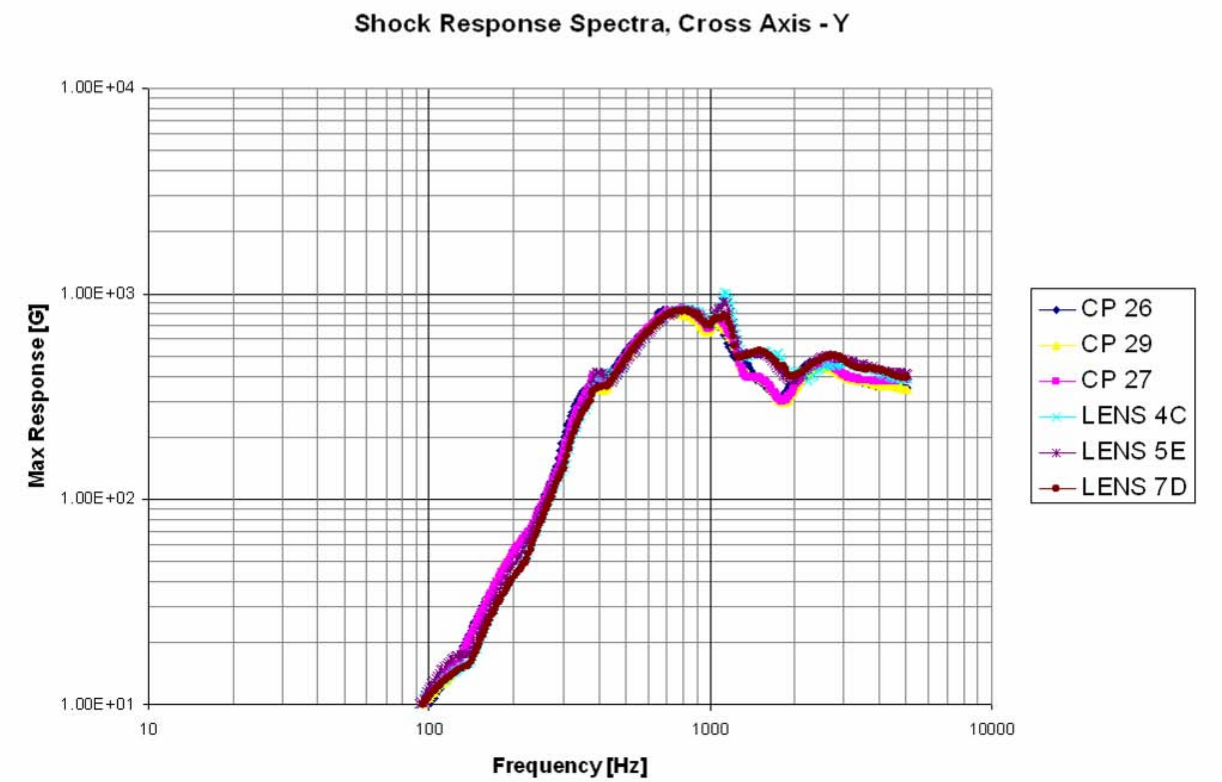


Figure 27. Shock Response Spectra as Measured in the Cross Axis Y Direction

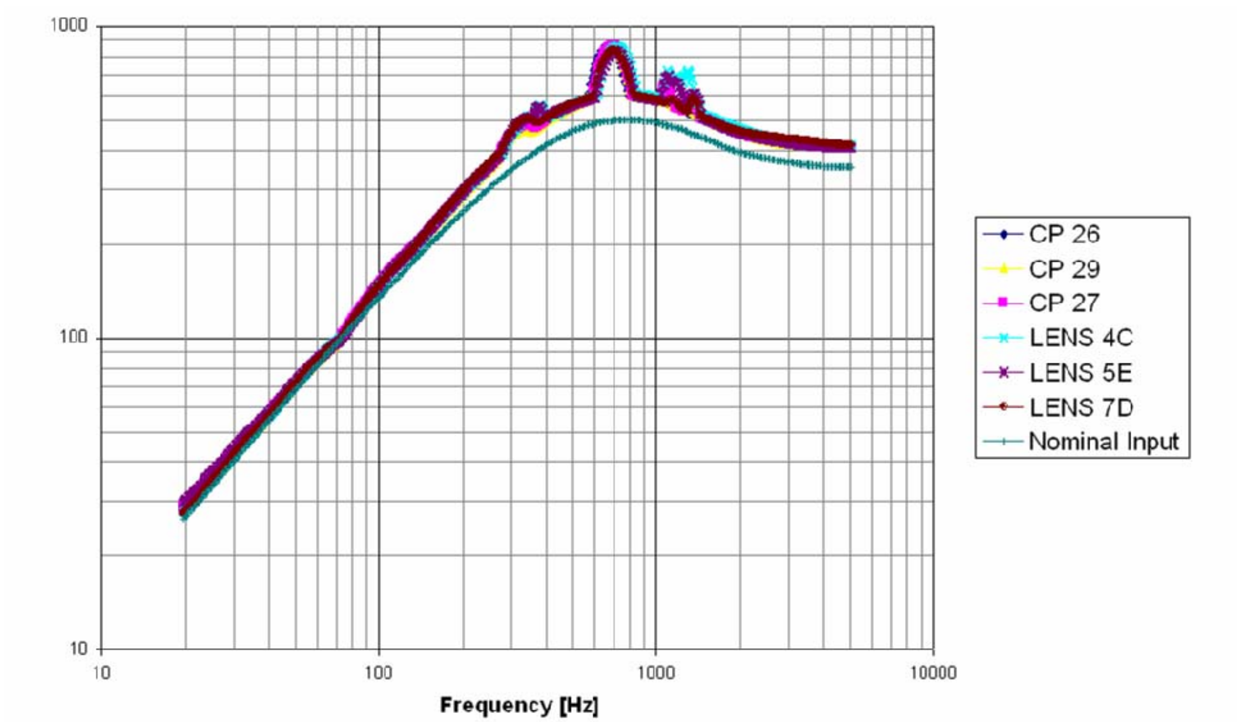


Figure 28. Shock Response Spectra as Measure In-Axis Z Direction

The parts were all measured by coordinate measuring machine both before and after the drop testing to identify any changes in geometry caused by the shock, but the parts showed no signs of deformation. This is as one would expect for a well-designed and analytically tested part. It did, however, further confirm the equivalency of the LENS and conventionally produced parts.

4.3. Statement of Equivalency

Throughout the project to qualify the LENS process, the design agency has been very helpful and supportive of the effort. The DA offered that LENS fabricated brackets could be put into "parallel path" or "piggyback" testing in the very expensive subsystem-level weapons environment tests. Because of the cost and time associated with the testing, it was absolutely necessary for the LENS parts to not jeopardize the conventionally produced parts which were the parts designated for WR production once system qualification was completed. To be able to include a LENS part, the LENS brackets needed to demonstrate equivalency with CP parts so that the designers would have confidence in their ability to meet the rigorous testing requirements. Based on the testing described above, the DA concluded that the parts are equivalent and would be acceptable for inclusion in subsystem-level testing. This approval is shown in Figure 29. Additionally, all of the LENS effort had been completed in time for the parts to be included in the tests. Unfortunately, the W80-3 LEP was cancelled and the tests will not occur. Despite this unfortunate turn, the LENS parts showed that the LENS process is a feasible alternative to other manufacturing processes when demanding requirements match the capabilities of the LENS process. This especially makes sense in the repair and modification of complex structures such as electrical housings.

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation

Livermore, CA 94551-0969

date: July 17, 2006

to: John Smugeresky

from: Simon Scheffel

subject: Comparison of Performance Characteristics between WR and LENS Fabricated Hardware

This Memo is in response to the information you shared with me recently regarding evaluation of a LENS-fabricated version of the D-Bottle Bracket (1E0125). As you are well aware, I was not the party, which requested this component be LENS prototyped. But, I am responding at this point in time, as I am now the system engineer that oversees this component.

From my perspective, a measure of success for justifying the LENS fabrication approach is a direct comparison of how these parts compare to a (WR) version, or control specimen. You have provided me with an overview of testing done to samples (both LENS and traditionally fabricated), which includes Modal and Shock testing (conducted by Jim Lauffer and Mike Jew). These tests were based on direction provided by Michael Lameraux, the former systems engineer overseeing the D-Bottle Bracket. Furthermore, these tests were driven by criteria in the Environmental Specification (ES), which defines normal and abnormal environmental conditions for the W80-3 system (ES1E0003, Rev. C; 4/28/2004). The overview of these tests concludes that the modal frequencies of WR and LENS versions of the D-bottle bracket are within 5% of one another in a "free" (hanging) state. Additionally, a strong correlation is present between WR and LENS samples in the Drop Test results shown.

The results described above suggest that LENS produced parts should meet the requirements for the D-Bottle Bracket application. Assuming LENS would offer an advantage in terms of development time or cost, I would pursue additional WR testing to qualify LENS-fabricated parts just as I would for units, which are conventionally machined.

I am excited to see an appropriate fit for this technology, and am pleased to be an advocate in supporting LENS as a feasible approach to prototyping and development of WR-quality hardware.

Thanks,

S. Scheffel

Simon Scheffel
Bowl PRT Lead
Org 8241, W80 Systems Engineering

Exceptional Service in the National Interest

Figure 29. Memo from DA Stating Equivalency of LENS-Produced D-Bottle Bracket to Conventionally Produced Brackets

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5. CONCLUSIONS

The LENS Qualification Technology Investment Team set out to show the applicability of LENS-produced components to weapons applications. The goal of the project was to qualify the LENS process, use LENS to build weapons components, and test those components against conventionally produced parts. This set of tasks was aimed at giving confidence to designers regarding the capability of LENS and its applicability to weapons applications. This confidence would in turn give designers another tool to use in the manufacture, repair, and modification of complex weapons parts for stockpile applications.

The testing showed LENS parts to have similar mechanical properties to conventionally produced parts. The LENS parts also showed the ability to be machined to final part dimensions and then used in weapon environment testing. The LENS parts, tested for structural dynamics through modal analyses and Haversine shock testing, demonstrated nearly identical response to conventionally machined parts. This equivalency was noted by the DA and the parts were approved for parallel path testing in costly subsystem-level environmental testing. Unfortunately, the W80-3 LEP was cancelled before this testing could occur, but the project is still a success for demonstrating the capabilities of the LENS process for utilization in high rigor applications.

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