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DEVELOPMENT OF LASER ENGINEERED NET SHAPE (LENS) ADDITIVE MANUFACTURING FOR REPAIR

P.S. Korinko

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DEVELOPMENT OF LASER ENGINEERED NET SHAPE (LENS) ADDITIVE MANUFACTURING FOR REPAIR

Paul S. Korinko
Savannah River National Laboratory
Aiken, South Carolina, USA

ABSTRACT

Laser Engineered Net Shape processing was evaluated as a means to repair scratched gas sample bottles and mis-machined test bases. Defects to be repaired were intentionally introduced. These defects simulated scratches and holes that had been either over bored or misaligned. These parts were repaired using LENS and then tested in the baseline, as damaged, and hydrogen charged conditions. The effect of LENS repair was not detrimental to the properties of the components. Further development work and implementation of the process is recommended.

INTRODUCTION

Manufacturing processes and quality assurance methods are being continuously improved with the advent of new technology and equipment, however, human error, equipment malfunction, and wear still occur. These problems can be addressed by developing new methods and approaches to repair and rebuild mis-machined and worn parts. It is common practice to add virgin metal to worn and mis-machined parts using welding, brazing, thermal spraying, plating, etc. (1 – 13). Repairs for specific products and items have been implemented across a broad range of industries from aerospace to wire industries and all industries in between. The introduction of new technologies is often resisted. There is an "energy barrier" to overcome to change the status quo and implement new technology, however, with reduced budgets and compressed times scales, government and industry must become a more agile and willing to adopt new technologies more rapidly.

Within the Department of Energy there is need to develop a Responsive Infrastructure to respond to evolving threats, develop new hardware, and complete modifications of weapons components and tooling. With the broad acceptance of 3D solid modeling new technology can be deployed to design and fabricate parts that can be repaired or reused with modifications. Rapid Prototyping has recently been recast as "Additive Manufacturing" due to improved material and processing capabilities. Additive Manufacturing is a repair technology that has been and should be continually developed for deployment.

While the technology was originally developed as a method for rapid prototyping, technology advances in machine control, power supplies, materials, and processing control have encouraged the technology to advance to a situation where it can be used for limited production runs, to make complex tooling, to effectively "print" parts, and to be used for localized repair.

A task was conducted to examine the additive manufacturing using the LENS process for repair. This task included several subtasks and addressed issues. The selection of components, materials and test methodologies were considered. The incorporation of any repair technique must include criteria for acceptance testing. In this case, the general task was to create the defects, correct the defects and test baseline and hydrogen charged materials for comparison. Bulk LENS prepared material was also characterized.

This paper will describes the use of LENS® as a repair technology in the field of Additive Manufacturing. It is worth noting that laser cladding has been used as a commercial repair technique (14, 15). Two advantages of laser cladding over conventional repair techniques include 1) minimal dilution of repair material with the substrate such as occurs with weld repairs, and 2) a metallurgical bond rather than a mechanical bond such as occurs for thermal spray repairs. Thus laser cladding repair offers potentially unique conditions that may permit addition of more suitable materials over the damaged substrate. This additive material could be tailored to the application since there is little dilution. One could conceive of using a softer material deposit if fretting is the issue or a harder deposit if wear is the issue.

In general, LENS® can be used in one of two modes: 1) complete part/component building or 2) repair/modification of existing parts/components. The focus of this paper is the development and qualification of the LENS® technology to repair existing parts or components. The assumption for the repair was that the components were damaged or mis-machined and the repair was to bring them back into compliance with the specification/drawing. The parts, a gas sample bottle and reclamation weld test bases, are Type 304 stainless steel so the additive material was also Type 304 stainless steel. After repair, the components were machined to tolerance and tested per the acceptance testing requirements. This document provides an overview of the LENS® technology and a detailed discussion of the capability of the process to repair mis-machined or damaged components and demonstrates the hydrogen compatibility of the bulk LENS® material as well as the repair application.

NOMENCLATURE

AM – Additive Manufacturing
DOE – Department of Energy
LENS – Laser Engineered Net Shape
Nd-YAG – Neodymium – Yttria-Garnet
RP – Rapid Prototype
SEM – Scanning Electron Microscope
SRNL – Savannah River National Laboratory

EQUIPMENT DESCRIPTION

LENS is one of the original AM systems. It uses coaxial powder injection to provide material for build up or repair. The newly injected powder and a fraction of the previously deposited material are fused during the laser pass. Other systems that may be used for AM apply the powder in in layers, bed processes. In these systems, a layer of powder is applied and the laser is selectively rastered over it, in the desired part path, to densify the component. Excess powder is removed after laser sintering. In the case of LENS only the powder that is injected is melted. There are advantages to both processes with respect to material use, rate of build-up and ultimate properties. A detailed description of the LENS process is provided in ref. 17. A schematic of the LENS process is shown in Fig. 1. The laser beam is centered in the gas nozzle. The powder feeds from the sides of the nozzle and is melted, the process parameters that are critical to the repair quality are the hatch width, laser energy, gas type, gas flow rate, powder type and powder feed rate. The repair work was conducted in a purified argon atmosphere that had approximately 5 ppm oxygen. A Nd-YAG continuous wave laser provided the heat source and parts were held in place with the appropriate tooling.

Figure 1 shows the arrangement to build large free standing structures; however, this application required smaller areas to be repaired, like the gouge shown in Figure 2. In order to deposit new materials in the areas of interest, the defect geometry was defined and the laser was programmed to repair the mis-machined area.

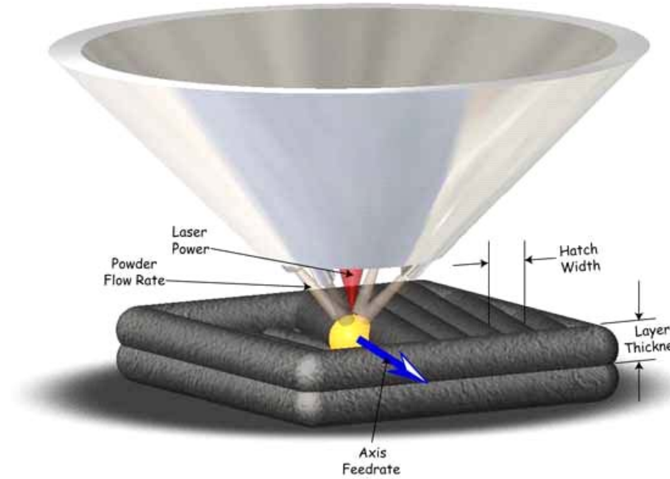

Figure 1. Mock-up of the LENS process showing the critical process parameters.

EXPERIMENTAL

The LENS parameters, powder feed rate, travel speed, laser power, etc. used to fabricate a test block and the repair conditions are listed in Table 1. The repair conditions were based on the initial preparation conditions. Due to time constraints, the repair conditions were not optimized for either the defect geometry, sample preparation, or process conditions.

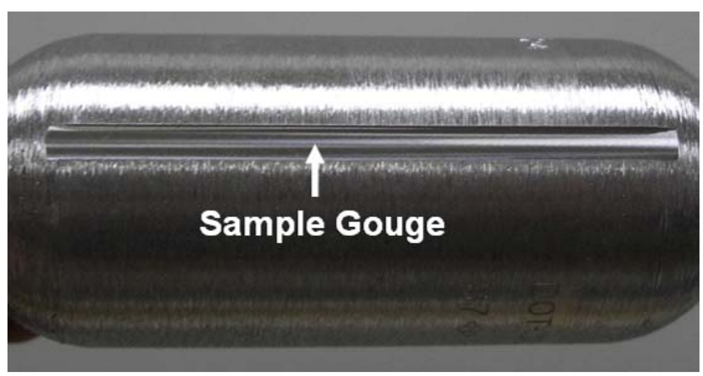

Figure 2. Defect simulating a deep scratch on a gas bottle, the gouge was created by milling 0.25 mm or 0.51 mm deep gouges 1.1 mm wide.

Type 304 stainless steel gas sample bottles were milled to have defects that were 0.25 mm deep and 2.5 mm wide and 0.51 mm deep and 2.5 mm deep. The defects had parallel sides and ran the length of the 500 ml bottles. A typical bottle "defect" is shown in Figure 2. The defect was LENS repaired and then excess material was removed using conventional machining, single point turning. The machining was stopped after removal of the excess LENS deposited material so that the wall thickness was not reduced.

Table 1. LENS conditions used to build bulk samples and for repair of reclamation bases and gas sample bottles.

Parameter	Block	Reclamation Base	Gas Sample Bottle
Powder Flowrate (gal/min)	23	23	23
Laser Power (W)	355-480	535	NM
Filter (%)	80	70	70
Axis Feedrate (in/min)	22	22	22

A second type of defect is represented by milling an oversized bore for a flat bottomed hole in a reclamation test base. The reclamation base is used to simulate a hydrogen storage vessel that is fabricated with a nominal 6 mm side bonded solid state resistance forge weld. This type of defect represents a hole that could be bored eccentrically or simply bored too large or too deep. A sketch of the part and LENS repair fill orientation is shown in Figure 3. The center diameter for the repair parts were increased by 0, 0.38, 0.76, and 1.14 mm and were filled using the parameters listed in Table 1. Note that the process parameters evolved as knowledge was gained for these specific repairs. For instance, the rotational speed was increased as material was deposited at the center of the reclamation base and a protrusion was observed, also the powder feed was decreased to avoid the build-up at the center

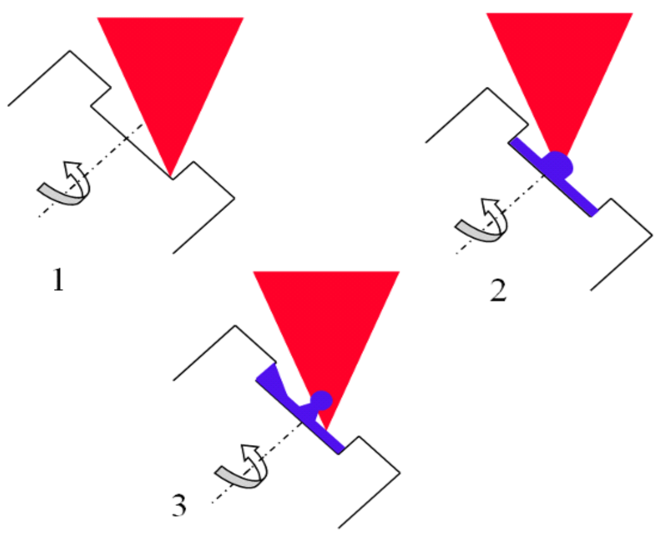

Figure 3. LENS build-up orientation to minimize formation of a central build-up on the repaired parts. The rotational speed was increased to minimize the effect.

which ultimately interfered with the material deposition. After LENS repair, the excess material was machined to provide a nominal 6 mm bore diameter with a 2 mm depth. The parts were cleaned and a standard diameter fill stem was welded in place. The welding conditions used for the LENS repaired bases were consistent with the production process parameters, 5.56 kN axial force, 11,400 Amperes, and 25 AC cycles (60 Hz nominal). These samples were burst tested in the as-fabricated and hydrogen charged condition.

Mechanical properties were measured using two methods. Miniature dog bone tensile samples were tested in an Instron 1125 mechanical test system in the as-fabricated and hydrogen charged conditions. The tensile samples were wire electrical discharge machined (EDM) from the ingot of material. The samples were 0.51 mm thick with a 12 mm gauge length and a 31.7 mm overall length. The tests were conducted at 0.051 mm/min in air. Elongation was measured using a clip gauge. The bottles and mis-machined bases were hydro-burst tested using a water filled vessel followed by hydro-pressurization. All of the test samples were pressurized to failure in approximately one minute. The pressure at failure and maximum diameter were determined.

Samples were hydrogen charged by placing them in a 3.78 liter high pressure vessel. The vessel is rated at 24.1 MPa at 343°C and is fabricated from 300 series stainless steel. All of the parts were placed in the vessel which filled it to about 60% full. The air was purged from the vessel by flowing argon through it for 20 minutes. The vessel was pressurized with 10.3 MPa of hydrogen at room temperature then heated to 325°C. The internal pressure reached 17.2 MPa. The samples were charged for about 4 days. The time and temperature should have resulted in 95% saturation of the stainless steel based on a differential diffusion calculation. The samples were cooled under hydrogen pressure, removed from the vessel and tested within eight hours of removal.

Selected samples were cut and mounted and examined using standard metallographic techniques. Burst test samples were examined using scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

The LENS repaired gas sample bottle in as repaired and as machined conditions are shown in Figure 4. The LENS repair was nearly the same diameter as the original bottle diameter, although there was some shrinkage around the LENS repair. A cross-section of the LENS repair is shown in Figure 5. This image shows that the LENS repair did not completely fill the original notch. There was inadequate heat applied to the fuse all of the powder to the bottle. It is surmised that altering the shape of the defect would improve the ability to repair notch type defects. Some potential process improvements include using a 30 to 45 degree angle on the edges of the "scratch" would reduce the interaction of the particles with the sidewalls and help direct the heat into the base of the notch and rastering at 90° to the defect. Unfortunately due to programmatic and budgetary restraints, no opportunity was afforded for additional development and optimization.

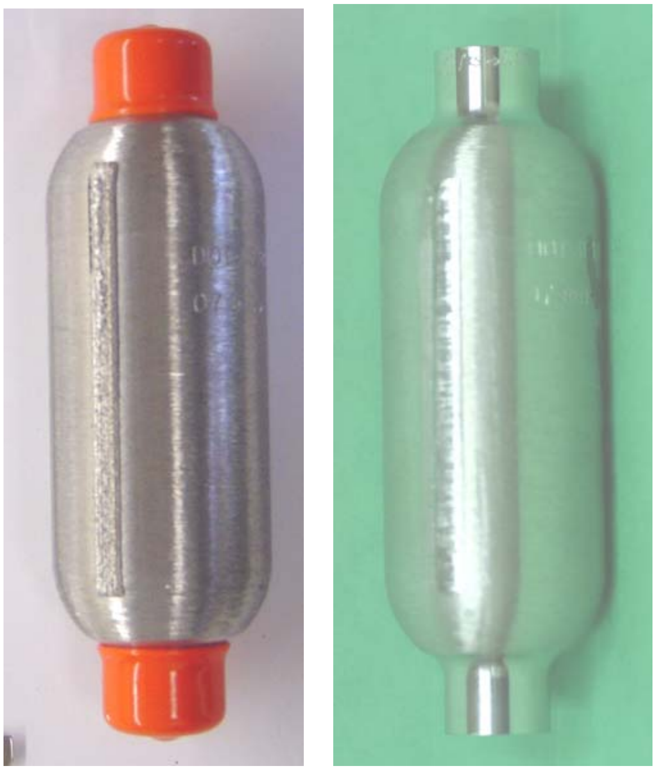

Figure 4. As LENS repaired gas sample bottle and after machining. The repair is visible but appears to be cleaned up.

Figure 5. LENS repair on gas sample bottle that had a 0.5 mm deep gouge.

The as-repaired condition of the reclamation test bases is shown in Figure 6 for various levels of overbore. The center of the sample exhibits a protrusion, as indicated in the experimental section. The visual appearance of this material suggests less than ideal particle melting and bonding. The material machined nicely and all the poor quality material at the center of the reclamation bases was removed prior to welding fill stems, a fully repaired, machined, and welded sample is shown in Figure 7. The heat band and slight extrusion of material around the weld are consistent with typical production welds. The fill stem foot diameter is oversized by 0.63 mm. This amount of interference has been successfully used for welding gas bottles. The bond characteristics for a typical reclamation weld are shown in Figure 8. The stem foot undergoes shear displacement and exhibits a slight protrusion. The entire length of the insert is not necessarily bonded and depending on the alloy, the production limits range from 50 to 70% minimum bond. For the LENS repaired test articles, no weld acceptance testing was done due to insufficient assets, however, select samples were examined after burst testing.

Figure 6. LENS repaired reclamation base with an initial bore that was 1.14 mm oversize.

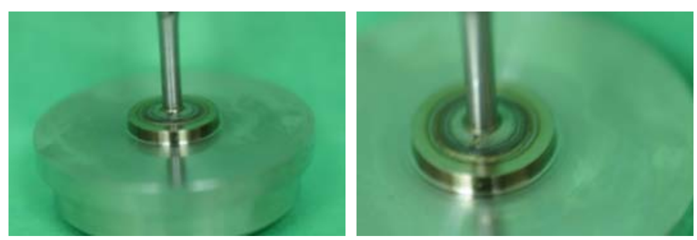

Figure 7. LENS repaired, machined and welded test base.

The tensile test results for the bulk LENS material are shown in Figure 9. The tensile results indicate a slight increase in yield strength of the LENS material compared to the baseline shim stock. There is significant reduction in elongation for the LENS material. A better comparison for the as deposited LENS material might be a comparison to cast compositions of 304L stainless steel, i.e., CF-3 which still has approximately 50 – 60% elongation in the as solution annealed condition (18). The tensile properties after hydrogen charging indicate a slight reduction in elongation. This decrease is consistent with materials that are only slightly affected by hydrogen charging (19).

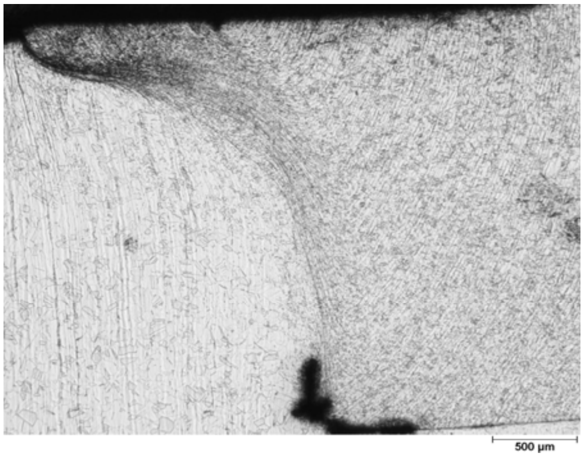

Figure 8. Typical test base to fill stem weld showing displacement of foot stem material, some near melting of the stem and deformation of material.

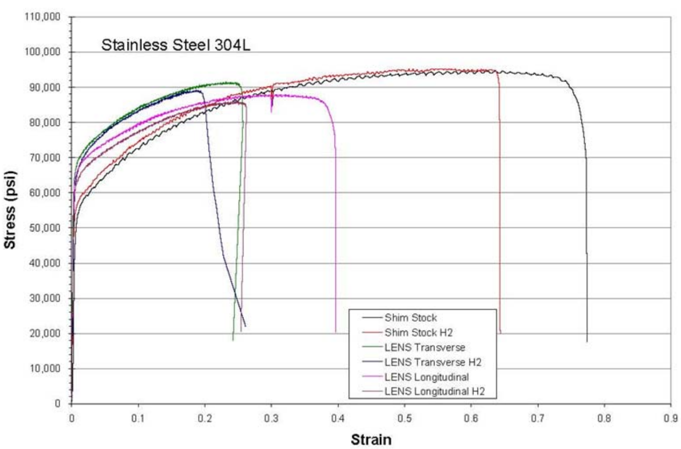

Figure 9. Tensile Test results for SS shim stock and bulk LENS material as-fabricated and hydrogen charged conditions.

The repaired reclamation test bases were hydrogen charged as indicated previously. The samples were hydro-burst tested. All of the samples failed in the stem wall, as is expected for the geometry. The wall is about 0.76 mm thick, compared to the welds which are a minimum of 1.1 mm long. If one assumes that thin wall pressure vessel equations are valid for the hoop (σ=pr/t) and axial stresses (σ=pr/2t), then the tube wall will fail at a pressure of about half that required for the foot, assuming the same properties for both. The burst results are shown in Figure 10. Due to the sample and weld geometry this is not a very discriminating test to determine the relative merit of the repair, however, it is one acceptance criteria.

The gas sample bottles were tested in three different conditions. The effect of the notch on the burst pressure and deformation characteristics were evaluated by testing the as-received bottle, bottles with machined notches and notched

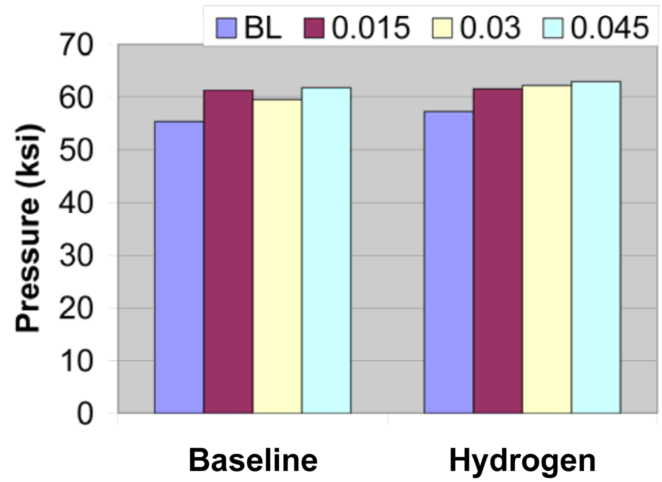

Figure 10. Burst test results for baseline and hydrogen charged reclamation test stems. No measurable effect was observed.

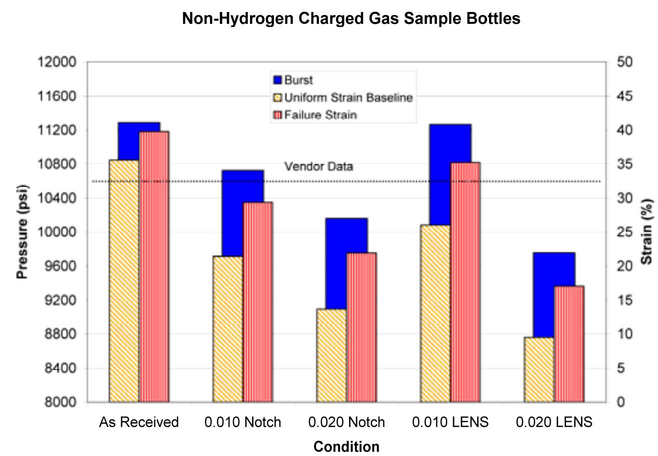

Figure 11. Burst test results and metrics for gas sample bottles in the as-received, as-notched, and LENS repaired conditions.

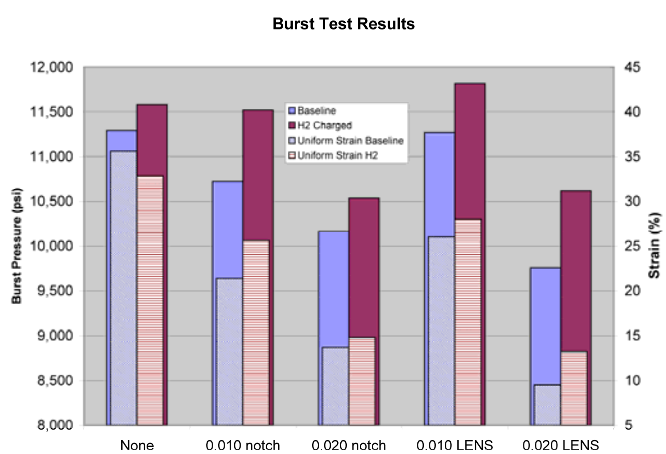

Figure 12. Burst test results comparing the effects of hydrogen on baseline and repaired gas sample bottles.

bottles that had been LENS repaired. The burst pressure, uniform ductility and failure strain were determined for these conditions. The uniform strain is estimated based on the maximum diameter measure post-test while the failure strain is estimated based on the measured maximum bulge at the failure. The uniform strain is likely a better measure of the ductility. The summary data for the baseline conditions are shown in Figure 11. These data show that the presence of the notch reduces the burst pressure and ductility. The 0.25 mm LENS repaired sample exhibited a burst pressure ductility that increased over the as-notched, but did not restore them to the as-received condition.

The gas bottles that were notched, and notched then LENS repaired and hydrogen charged were also burst tested. The hydrogen charged samples exhibit interesting results. The baseline data shown in Figure 11 is repeated in Figure 12 along with the hydrogen sample data. The hydrogen charged samples show some strengthening due to hydrogen charging. This

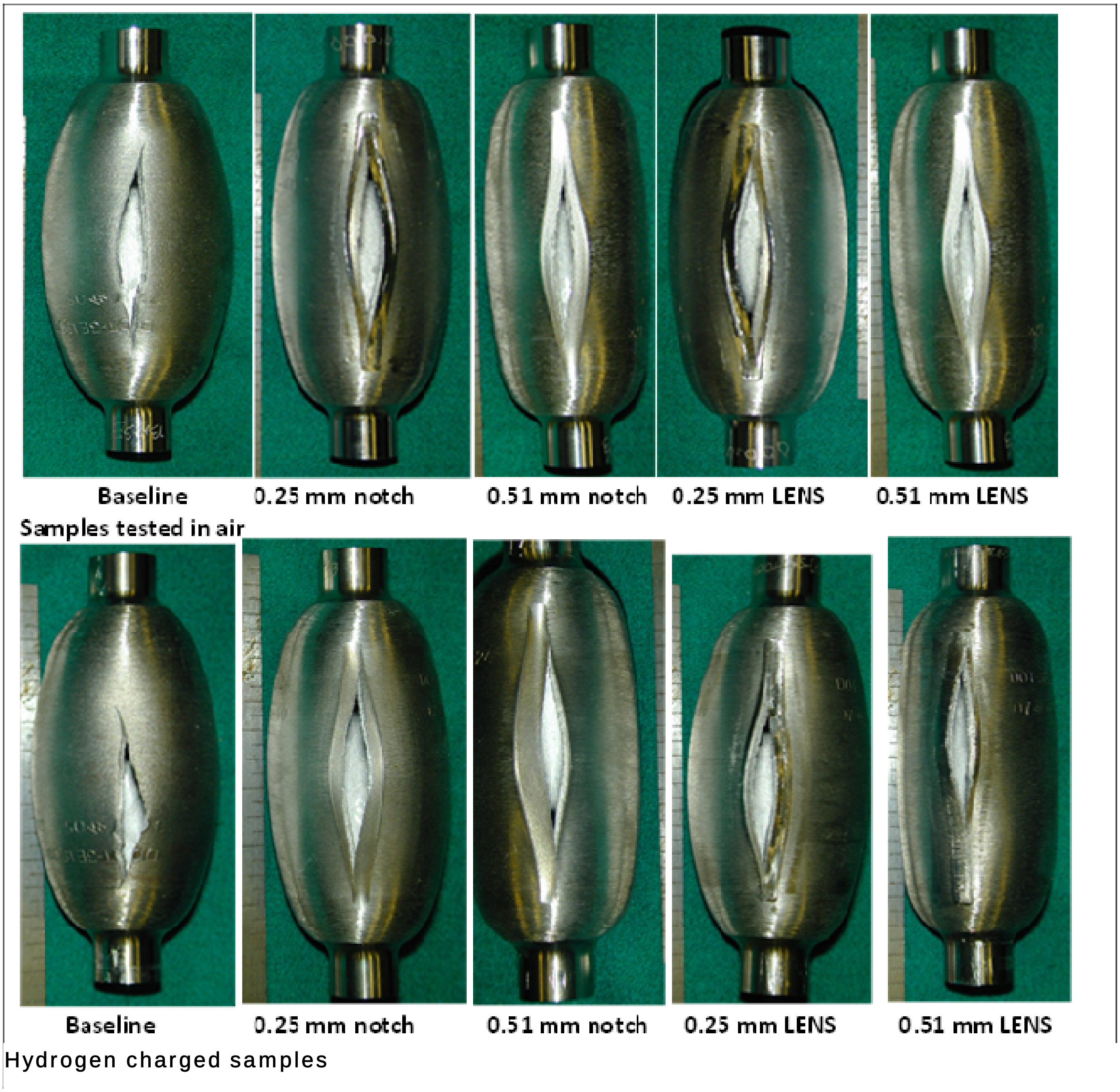

Figure 13. Appearance of baseline and hydrogen charged gas sample bottles in the as fabricated, damaged and LENS repaired condition.

phenomenon has been seen in previous tensile test work (19). The hydrogen data plotted in Figure 12 is the average of the two points for the conditions charged and tested. As was the case for the baseline samples, the presence of notches reduced the burst pressure for hydrogen charged samples, although the fractional reduction in burst pressure was less for the hydrogen charged samples than the baseline. The burst ductility is lower for the hydrogen charged samples with notches.

The sample with the 0.010 inch (0.25 mm) notch that was LENS repaired actually demonstrated a slight increase in strength over the baseline condition for hydrogen charging and essentially no loss from the baseline value. Both the 0.020 inch (0.51 mm) notched and 0.020 inch (0.51 mm) notch and LENS repaired sample exhibit burst pressures and uniform strains that are similar in value.

The appearance of the burst tested gas sample bottles exhibited the expected failure with the bottle tearing axially, in addition all of the samples with notches failed in the notch. There was one exception for the LENS repaired samples with one of the 0.25 mm LENS repaired samples failing in the vessel body away from the repair, indicating that the repair was excellent and that it had no adverse impact on strength. Photographs of selected burst tested vessels for both baseline and hydrogen charged conditions are shown in Figure 13. The change in sample diameter growth, i.e., direct indication of strain, appears lower as the extent of the defect increases, this feature is apparent in Figure 12 as well.

The fracture surfaces of the LENS repaired surfaces were also examined. The LENS material appears to have cracked axially with a width that is consistent with the hatch width (Figure 1) of the LENS build-up. Some of the samples exhibit a possible delamination from the gas sample bottle as well as between the interlayers of the LENS repair. This failure mode is likely indicative of the non-optimized deposition method and deposition conditions, including the axially deposit into a blind defect. The cracking and onset of delamination of sample 0.010 LENS H_2 that did not fail in the LENS repair area is shown in Figure 14. Some unmelted particles are also visible in the SEM fractograph. These unmelted particles are symptomatic of the rush to repair to meet schedule. Sample preparation to improve the repair methodology would have included development of an angled groove rather than a sharp edge, 90° angle, to avoid particle entrapment near the molten pool, multiple raster directions and higher laser energy to improve the interlayer melting may also improve the LENS repair.

SUMMARY

Additive Manufacturing using the LENS process to repair mis-machined and gouged sample gas bottles is a feasible technology. The hydrogen charged and burst tested reclamation stems failed in the tubing, as expected, for materials that exhibit thin walls relative to the axial endcaps. Reclamation weld conditions were directly transferred from the

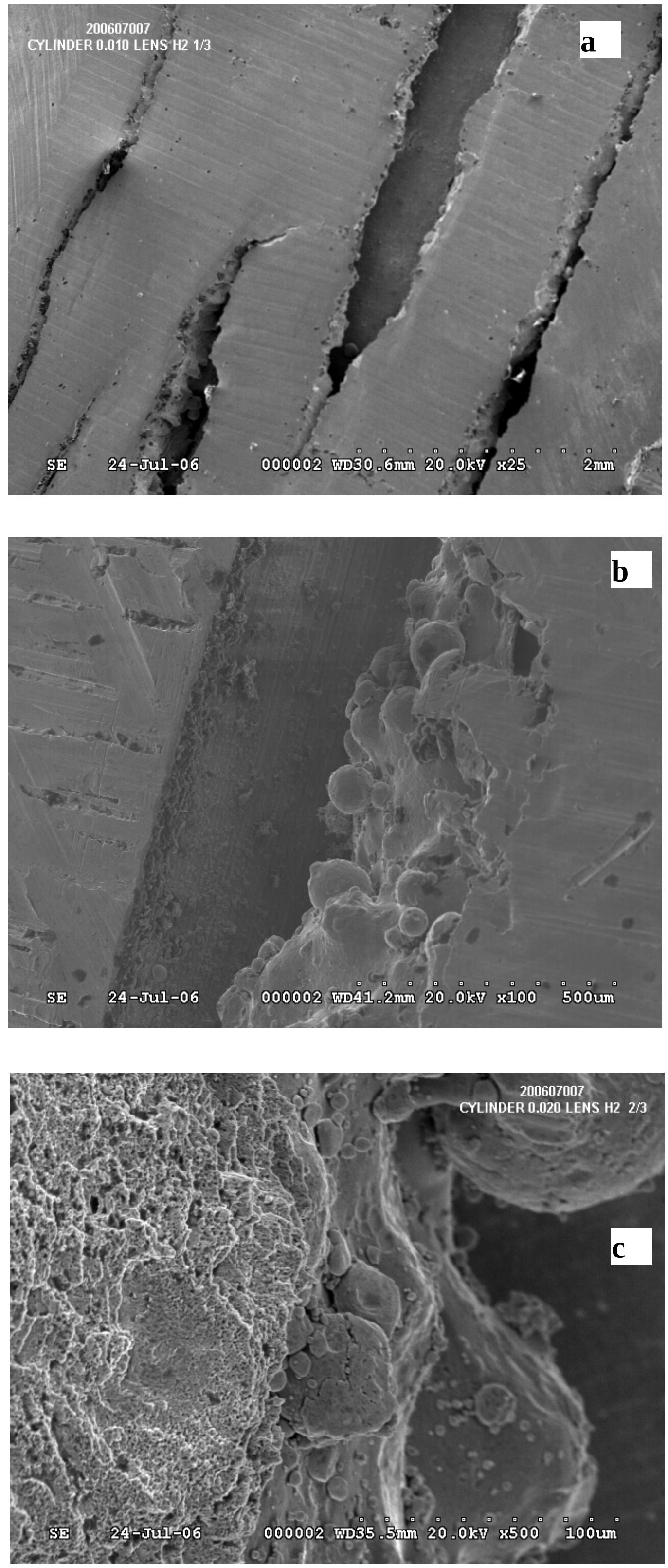

Figure 14. Burst test fractography for a) 0.25 gouge LENS repair H_2, b) 0.51 mm gouge LENS repair c) 0.51 mm gouge LENS repaird H_2 charged.

standard reclamation test bases to the LENS repaired test bases without any modifications.

Sample gas bottles with machined defects were successfully LENS repaired for dimensional purposes. Gas bottles were burst tested to failure in the as-machined, as repaired, and hydrogen charged conditions. All of the notched and LENS repaired bottles failed in the notch, except one bottle with a 0.25 mm deep LENS repaired notch. Inadequate fusion between the LENS repair and base metal is likely the cause of the failure mode.

The sample gas bottle repair would have benefitted by being optimized for the defect type and geometry. Additional heat was needed to improve the repair tie-in with the gas bottle. Burst testing of the gas bottles indicated that there was a stress riser at the corner of the groove. This may have contributed to the reduced ductility of the machined as well as the repaired bottles.

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LENS® is a registered trademark of Sandia National Laboratory.

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