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Abstract

New methods of repairing mis-machined components are always of interest. In this study, an innovative method using Laser Engineered Net Shape™ (LENS®) forming was used to repair intentionally mis-machined test articles. The components were repaired and subsequently hydrogen charged and burst tested. The LENS repair did not have an adverse effect on the solid state weld process that was used to repair the components. Hydrogen charged samples failed in a similar manner to the uncharged samples. Overall, the prospects for LENS repairing similar products are favorable and further work is encouraged.

Introduction

Laser Engineered Net Shaping ™ (LENS®) is a unique metal manufacturing technique that offers the ability to create fully dense metal features and components directly from a computer solid model. LENS offers opportunities to repair and modify components by adding features to existing geometry, refilling holes, repairing weld lips, and many other potential applications. The material deposited has good mechanical properties with typically slightly higher strength that wrought material due to grain refinement from the quickly cooling weld pool.

The LENS® process utilizes a laser and powdered metal to form metal parts from computer solid models. The basic system consists of a laser, a powder feeder, a set of motion controlled axes, a substrate material, an inert atmosphere, and a closed loop melt pool control system. A schematic of the process is shown in Figure 1. The laser is focused on a metal substrate creating a small molten pool. The powder feeder feeds powdered metal into a flowing argon stream which is directed into the melt pool by four nozzle tips. The powdered metal melts and then the melt pool solidifies as the axis moves the melt pool to a new location. When moved smoothly along a trajectory, a raised line is created. The computer model controls the creation of the part: the model represents the desired additional material as layers and each layer divided into lines. The repair or component fabrication proceeds by depositing material line by line and layer by layer.

Figure 1 also shows several of the most important process parameters which can be varied to change the properties of the part. The *Laser power* has to be sufficient to melt the powder but not so high as to ablate the material. In many instances, this is controlled by a closed-loop melt pool controller which applies a Proportional-Integral-Differential (PID) controlled feedback loop to maintain a constant area of the melt pool above some chosen intensity value. The *powder flow rate* is be controlled as well. More powder builds taller parts, but excessive powder flow can cool the melt pool to such a point that the metal powder is not fused, resulting in inclusions in the finished part. The *layer thickness* determines how much of the previous layer is remelted in the current layer. Too large a layer thickness will also cause the laser focus to advance too quickly for the material ending in a part that does not meet geometric requirements. The *hatch width* determines the amount of mixing between lines deposited within the same layer. And the *axis feed rate* determines how fast the melt pool cools in addition to affecting the height of the build by increasing or reducing the amount of time that the melt pool is available to receive powder at a certain position.

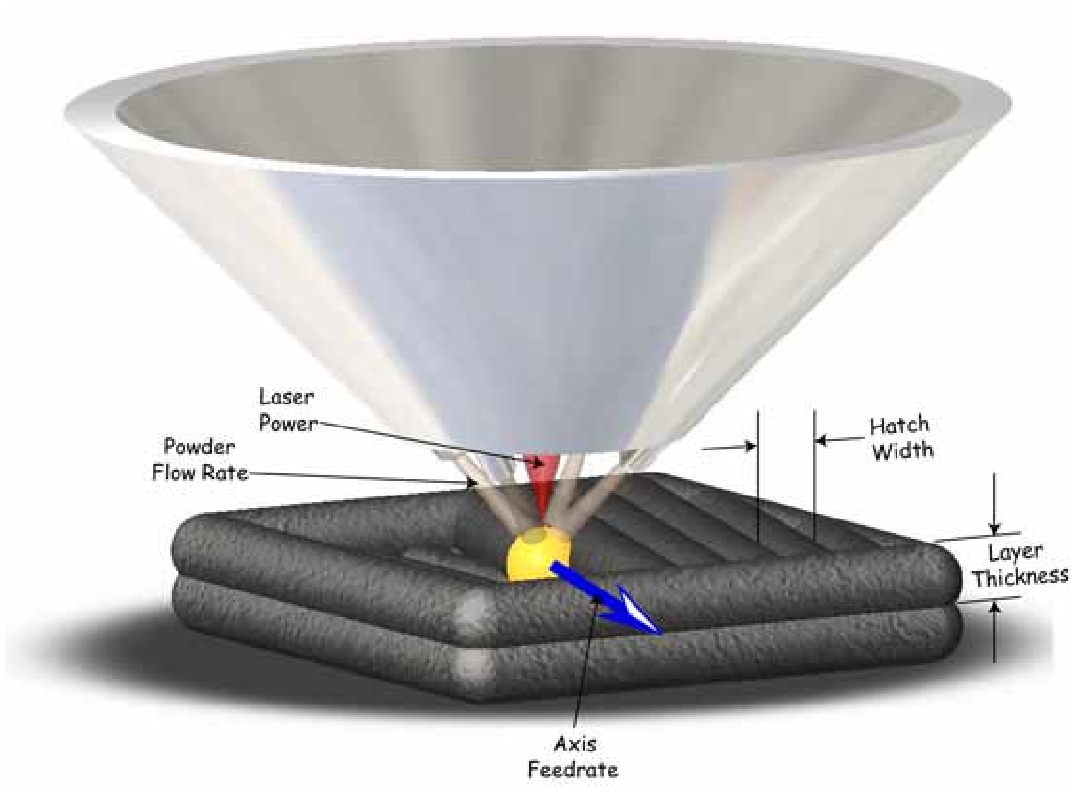

Figure 1. The LENS Process Showing Important Process Parameters

The LENS processing was performed at Sandia National Laboratory-NM, whose LENS machine is shown in Figure 2. The system is composed of 5 major subsystems. 1) The laser subsystem is of sufficient size to melt metal and the wavelength determines the laser's compatibility with specific materials. SNL's system utilizes a 1200W, continuous wave, Nd-YAG laser. 2) A closed loop melt pool control system that works closely with the laser to create consistent, repeatable process conditions. 3) A motion control system that uses coordinated movements of a set of axes. The motion must be controlled to create the component in the desired geometry. 4) A powder delivery system that typically consists of a stream of pressurized process gas, one or more powder feeders to meter powder into the gas stream, and a powder distribution system. And 5) a purified environment (typically argon with <5 ppm oxygen) is needed to assure the material deposited is as similar as possible to the composition of the metal powder used in the process.

The LENS® process has been demonstrated for a variety of materials and part configurations. LENS technology has successfully processed: 1) stainless steels—316, 304L, and 309S; 2) Nickel alloys— 718, 625, and 690; 3) tool steels—H-13, NU-Die EZ, MM-10, and CPM-10; 4) Ti-6Al-4V; 5) aluminum alloys; 6) gamma titanium-aluminide; 7) tungsten; and 8)metal matrix composites—WC in Co. Examples of some these typical LENS microstructures for these materials are shown in Figure 3.

Figure 2. Sandia National Laboratory LENS® Processing Machine

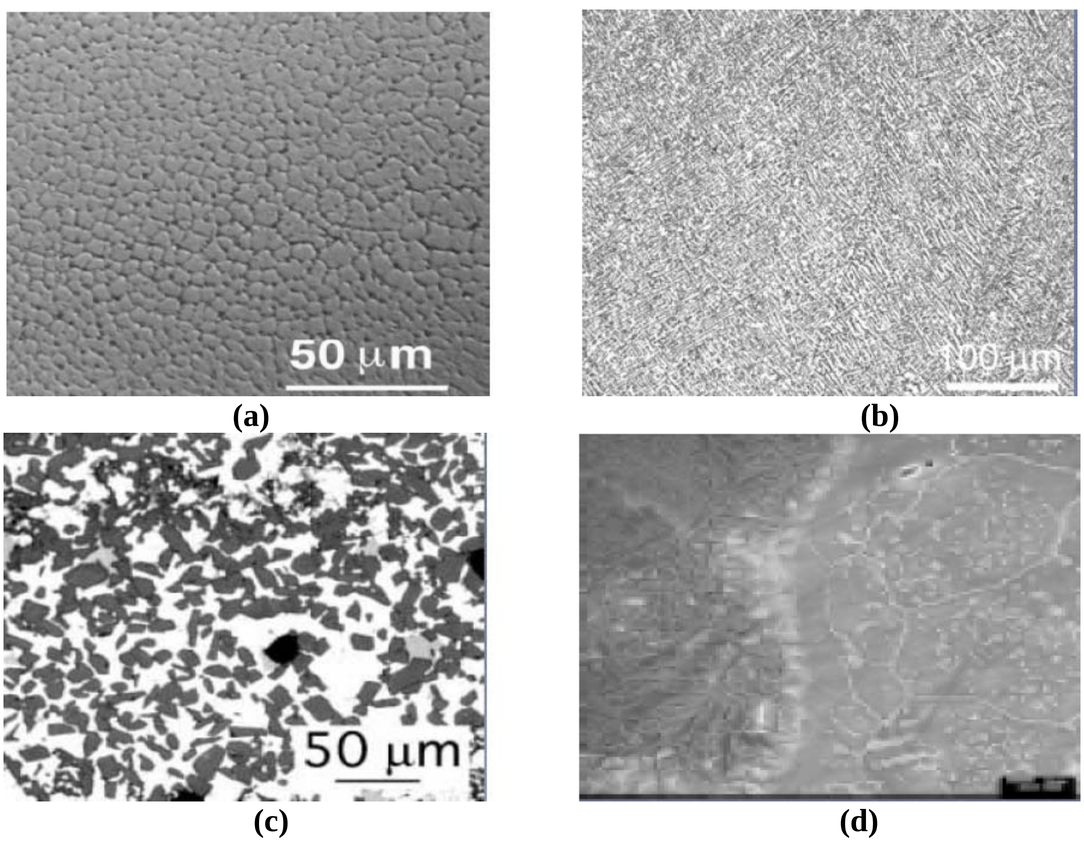

Figure 3. Typical Microstructures for LENS® Process Materials: a) 316 stainless steel, b) Ti-6Al-4V, c)WC-Co metal matrix composites, and d) Ni-Ti Functionally Graded Alloy Composite[1]

The LENS process was used to repair type 304L stainless steel "reclamation" weld test bases. These test bases were machined to simulate an eccentric hole boring operation, an over diameter boring operation, and an excessive depth machining operation. The LENS process was used in a non-optimal configuration to add replacement material that was subsequently machined, the samples welded, hydrogen charged, hydroburst tested, and metallographically examined.

Experimental

Type 304L stainless steel pieces were machined using conventional machining practices to a standard test geometry as shown in Figure 4a. To simulate both over diameter and eccentric boring, test bases were machined with bore diameters of 0.38 mm, 0.76 mm, and 1.14 mm. In addition, the nominal depth of the hole was excessive by 0.38 mm. These parts were parts were repaired using the LENS process to the condition shown in Figure 4b. The cone shape of the additive metal is due to repairing these samples by canting the test base at an angle, approximately 45˚, and rotating the part as the powder was fused. The decreasing radius of the repair area resulted in excessive build up at the center. This excess material did not cause any issues since it was removed during weld preparation.

Figure 4. Photographs showing the as machined and LENS repaired condition of the test bases.

The test base was welded using a series of components shown in Figure 5. A fill stem with a known "foot" diameter and depth is forced into the smaller diameter hole at a load of approximately 2250 lbs. A current of approximately 11,400 amperes is applied for 25 cycles of 60 Hz AC electricity. During this time the foot and test base heat to near the melting point of the metal and are deformed. Recrystallization and solid state diffusion occur during this 0.42 second period and a metallurgical bond is formed.

An Autoclave Engineers 1-gallon vessel was used to charge the samples with hydrogen. The vessel is rated at 3500 psi at 650˚F (343˚C) and is made from stainless steel. The vessel is heated with three heater bands that were heated using a PID controller. The samples were placed in the vessel with the gas samples on the bottom and the reclamation welded samples on top. The vessel interior was occupied by approximately 60% with stainless steel samples. The top was sealed and argon was used to purge air from the system and internal surfaces of the test articles. After about 20 minutes, hydrogen at a pressure of 1500 psig was introduced. The vessel was then heated to 617˚F (325˚C), the pressure increased to approximately 2500 psig and held for four days. These test conditions were deemed adequate to achieve greater than 95% hydrogen saturation based on permeation calculations using a finite difference computer program. The actual temperature and pressure data as well as the estimated saturation data are shown in Figure 6.

At least one sample of each manufacturing defect and LENS® repair condition that was not hydrogen charged was tested so the effect of hydrogen on the sample could be ascertained. The hydrogen pressure decay, shown in Figure 6, is likely due to some leakage as well as hydrogen uptake by the samples. The samples were cooled under hydrogen pressure, removed from the vessel in preparation for hydroburst testing.

The cooled samples were proof tested to failure using a hydroburst test facility. All of the samples were tested in a gun barrel to protect people and equipment. The samples were connected to the high pressure lines using high pressure fittings. The samples were then pressurized to failure within about a minute.

Figure 5. Typical fixtures needed to resistance forge weld a stainless steel stem into a test base.

A hydrogen charged and burst tested sample was examined metallographically. The sample was sectioned and polished, electrolytically etched with oxalic acid, and photographed at low and high magnifications. The welds from standard reclamation and LENS repaired test bases were compared

Results

A sample from an 8cm block of monolithic 304L LENS® materials fabricated by SNL was examined using light optical microscopy. The multi layered structure displayed in Figure 7 is characteristic of LENS® deposited materials and depicts the nature of the multi-pass deposition technology. It is assumed that a similar structure is present in the as LENS repaired structure of the test bases since these were fabricated using multi-layers to fill the machined areas.

Reclamation welds were made using standard weld conditions for 304L test bases as indicated previously, these are 2250 lbs, 11,400 A, and 25 cycles in air. All of the welds were successfully completed using these weld parameters. The fill stem / test base welded region is shown in Figure 8. There is a small amount of extrusion visible and relatively small thermally oxidized zone. These conditions are typical for this type of weld.

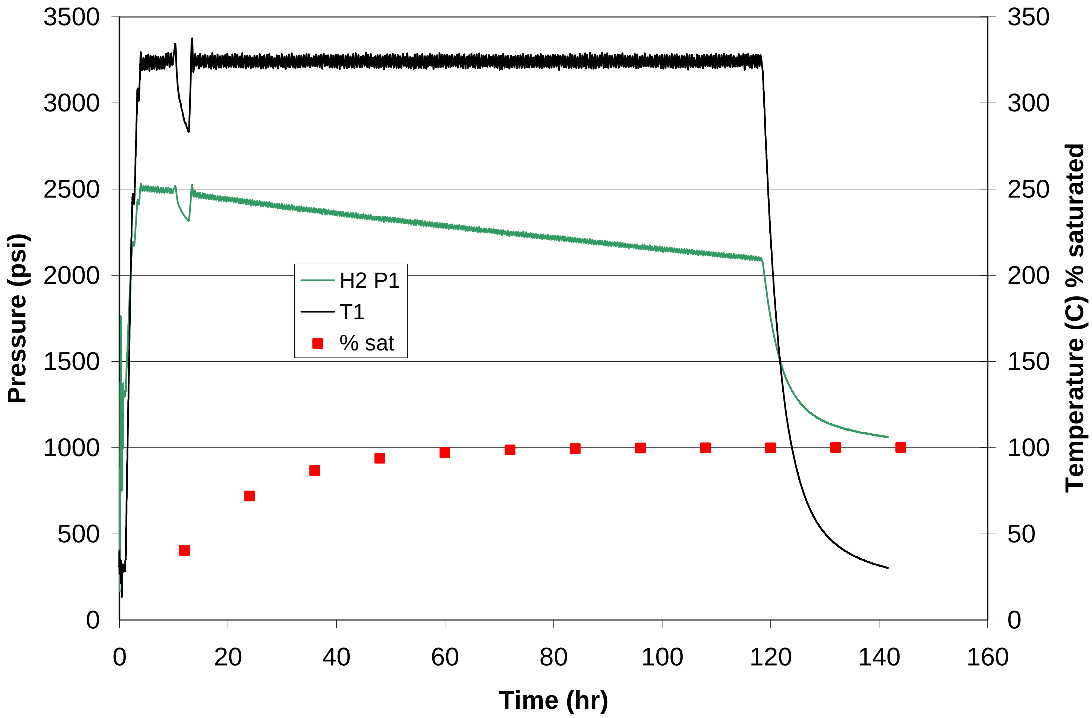

Figure 6. Charging conditions used the test bases

Figure 7. Typical microstructure of as processed bulk LENS material – Polished and etched (Electrolytically with 10% oxalic acid)

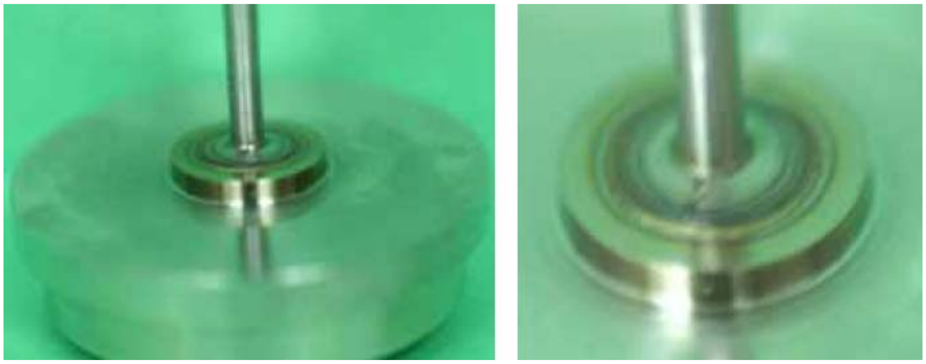

Figure 8. As-Welded Condition of a Reclamation Test Base.

All of the welded reclamation test bases failed in the fill stem tube wall at pressures between 58 and 62 ksi. These pressures are consistent with the nominal test values for the stems. A graph showing a comparison of the base line condition to the hydrogen charged condition is shown in Figure 9. The data exhibit an apparent increase in the burst pressure for LENS repaired parts. It is expected that this increase is due to lot to lot variation in the fabricated fill stem manufacture.

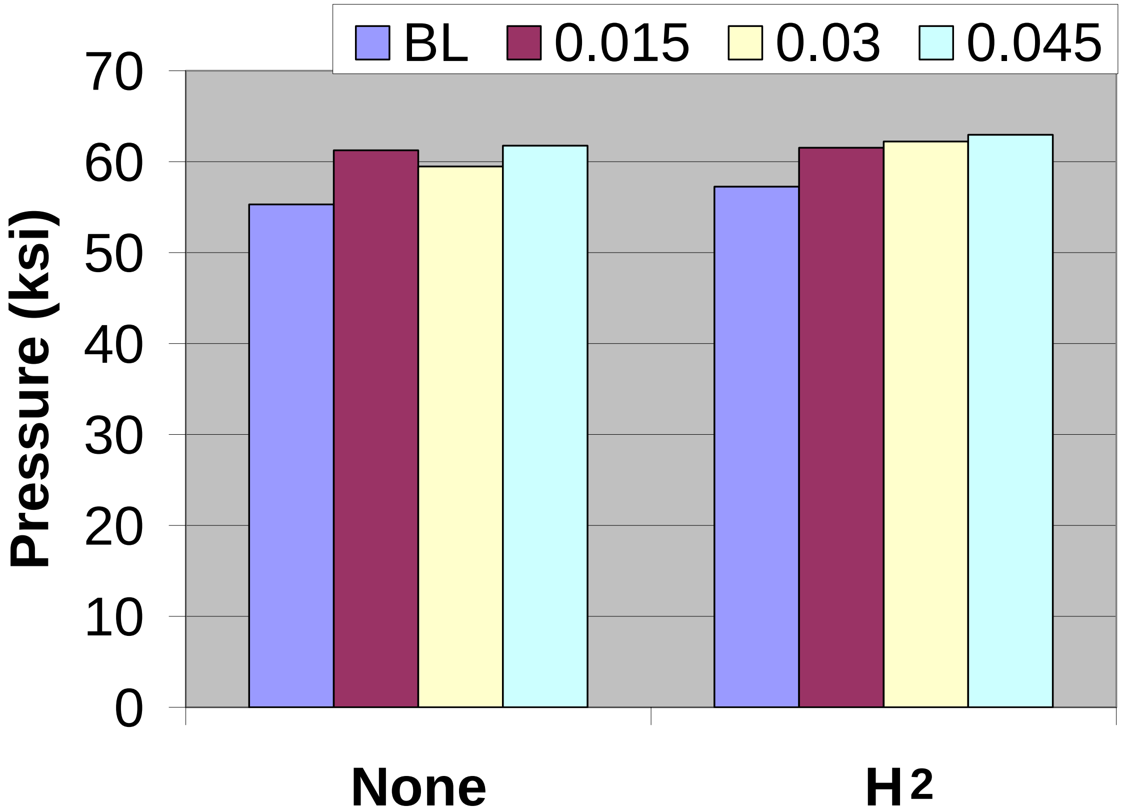

Figure 9. Burst pressure for reclamation test welds showing no effect of weld repair and little influence of hydrogen for the samples

None of the test bases failed near the weld, all failed in the tube wall. Typical tube wall failures for hydrogen charged and baseline samples are shown in Figure 10. These samples exhibit a classic fingernail type failure with evidence of ductile stretching in the tube wall. There may be less deformation for the hydrogen charged samples than for the baseline samples based on the extent of diametral expansion, but the extent of uniform deformation is difficult to characterize for such small diameters.

A representative sample from the 1.14 mm overbore and LENS repaired, welded and burst tested sample was examined metallographically. The typical form of the weld and more detailed microstructure can be seen in Figure 11. The low magnification image shows the presence of LENS repair material weld bonded to both the test base as well as the fill stem foot. The separation at the bottom of the foot is due to the pressure testing. Higher magnification images near the root of the weld and near the top of the weld indicate excellent bonding but there may be some tearing at the root of the tested sample.

A typical welded type 304L reclamation test base is shown in Figure 12. This sample exhibits fewer metallurgical features than shown in the LENS repaired sample. The main difference between the LENS repaired and the baseline sample is the extent of flow lines visible at in the joint.

LENS repaired and hydrogen charged and burst tested sample

Baseline sample burst tested
Figure 10. Typical samples after burst testing.

Figure 11. LENS repaired, welded, and burst tested sample. Original defect was 1.14 mm over bore.

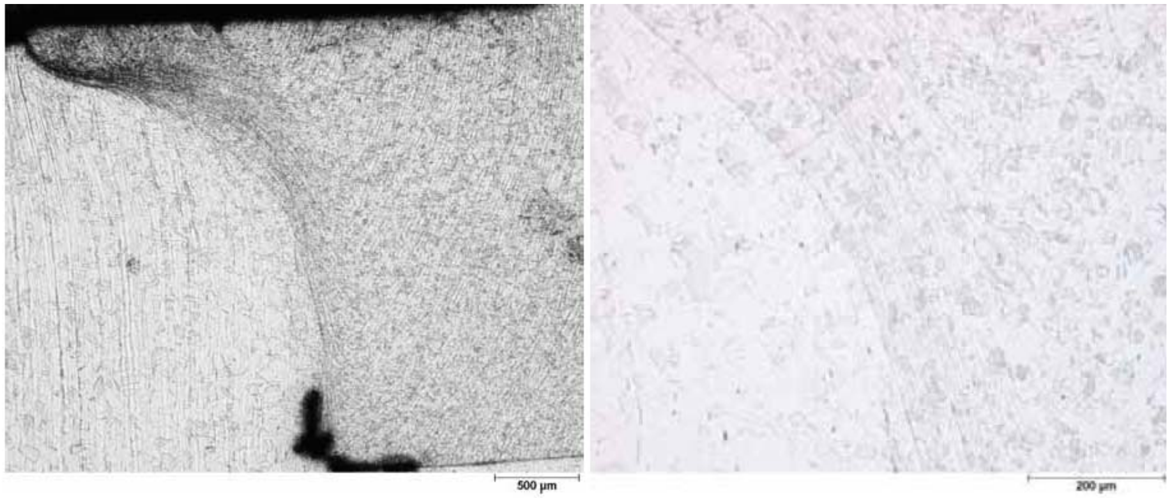

Figure 12. Typical reclamation welded type 304L stainless steel sample. Note that the flow lines along the weld interface are more prominent than for the LENS repair.

Summary and Conclusions

Reclamation test bases that were over bored for both diameter and depth were successfully repaired using the LENS® process. The material was machined and prepared in an acceptable manner for reclamation welding. Weld conditions identical to properly machined LF-7 test bases were successfully used for the LENS® repaired components. Baseline and Hydrogen charged reclamation test weld assemblies were burst tested with failures occurring in the fill stem at pressures consistent with expectations.

LENS® repair is highly suited for the repair of over bored reclamation components.

Acknowledgements

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