SAND98-2475C

UNDERSTANDING THERMAL BEHAVIOR IN LENS PROCESSING OF STRUCTURAL MATERIALS

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NOV 17 1998
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Abstract

In direct laser metal deposition technologies, such as the Laser Engineered Net Shaping (LENS) process, it is important to understand and control the thermal behavior during fabrication. With this control, components can be reliably fabricated with desired structural material properties. This talk will describe the use of contact and imaging techniques to monitor the thermal signature during LENS processing. Recent results show a direct correlation between thermal history and material properties, where the residual stress magnitude decreases as the laser power, and therefore thermal signature, increases. Development of an understanding of solidification behavior, residual stress, and microstructural evolution with respect to thermal behavior will be discussed.

This work supported by the U. S. Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Introduction

Direct laser metal deposition processing is a promising manufacturing technology, which could significantly impact the length of time between initial concept and finished part. For adoption of this technology in the manufacturing environment, further understanding is required to ensure routine fabrication of robust components with desired properties. This requires a complete understanding of the thermal history during part fabrication and control of this behavior. This paper will describe our research to understand thermal behavior for laser metal deposition. Previous work (1) describes the techniques used to study the weld pool thermal signature or solidification behavior, as well as the far field measurements to understand the thermal history in the bulk of the part.

The specific laser metal deposition technique used for this study is the Laser Engineered Net Shaping (LENS) process (2-6), in which a component is fabricated by focusing a laser beam onto a substrate to create a molten pool in which powder particles are simultaneously injected to build each layer. The substrate is moved beneath the laser beam to deposit a thin cross section, thereby creating the desired geometry for each layer. After deposition of each layer, the powder delivery nozzle and focusing lens assembly is incremented in the positive Z-direction, thereby building a three dimensional component layer additively.

It is important to understand the thermal behavior to reproducibly fabricate parts. The ultimate intent is to monitor the thermal signatures and to incorporate sensors and feedback algorithms to control part fabrication. With appropriate sensors and feedback, the geometric properties (accuracy, surface finish, low warpage) as well as the materials' properties (e.g. strength, ductility) of a component can be dialed into the part through the fabrication parameters. Preliminary details in correlating thermal behavior with processing results will be discussed.

Case Study with Stainless Steel

Thermocouple Measurements

A relatively easy way to obtain a thermal signature during processing is by inserting a thermocouple (TC) directly into the sample during fabrication. At the beginning of fabrication, the TC displays the initial temperature of metal deposition, whereas each subsequent measurement represents the thermal history for that position. Fine diameter (10 µm) Type C thermocouple wire was used for the measurements to ensure no reaction during deposition, and care was taken to insert the TC bead into the deposition zone for accurate temperature measurements. Solid rectangular samples (X =Y = 0.5", Z = 2") were fabricated out of stainless steel 316 (SS316) using a variety of powers, traverse velocities, and fill spacings (layer thickness and hatch). The process parameters are shown in Table I. For part fabrication, each layer consists of an outline, drawn first, and then a fill, or square cross section, generated by a simple raster pattern.

Table I. Parameters of fabrication for SS316 samples.

Parameter	#1	#2	#3	#4
Layer Thickness (in)	0.015	0.020	0.020	0.020
Hatch Spacing (in)	0.015	0.020	0.020	0.020
Traverse Velocity (ipm)	20	20	40	80
Power (W)	345	330	520	700

Figure 1 shows the in-situ temperature readings for layers 1, 5, 9, and 13 from a representative thermocouple inserted during fabrication of Sample #1. The thermocouple was inserted after an initial 0.5" of material was deposited to reach steady state conditions, where thermal effects of the substrate are nearly negligible. Each peak represents the thermocouple response as the laser passes over or near the thermocouple, from initial insertion to subsequent line and layer depositions. The thermal excursions dampen out when either the energy source moves away from the thermocouple during rastering in a layer or subsequent layers are deposited. After the initial peak in temperature, approximately 1800 °C, the heat is quickly conducted away in about 40 seconds to a nominal value of 400 °C for the first layer. This initial thermal signature should result in a solidification process producing a high strength, austenitic microstructure (minimal retained ferrite). Yet, for LENS processing, each subsequent pass reheats the previous layers, such that after the fifth layer is deposited, the first layer still receives a thermal hit of 900 °C. Following thirteen deposition layers, the thermocouple reads a nominal part temperature of 500 °C. After each deposition pass, the part cools down, but the part receives an integrated reheat which can affect the material properties including residual stress and mechanical strength due to tempering or aging effects.

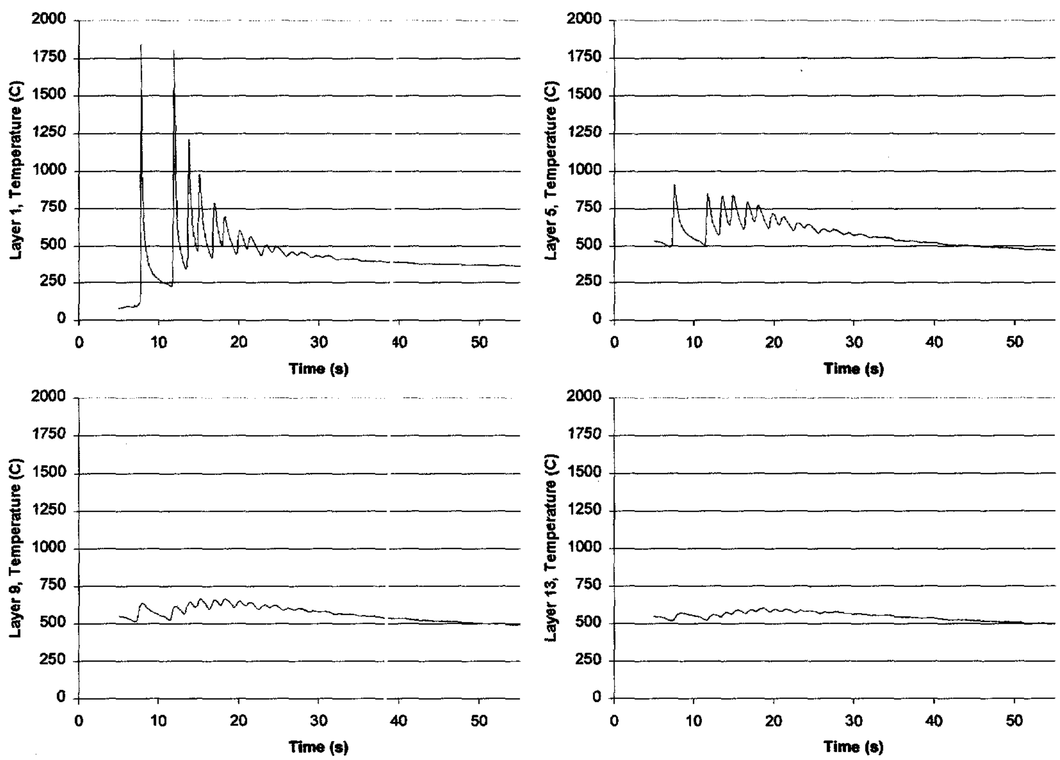


Figure 1: In-situ temperature readings for deposition layers 1, 5, 9, and 13 during LENS processing of Sample #1.

Residual Stress

Knowledge of the residual stress magnitude and distribution is important because of its effect on structural behavior. A holographic-hole drilling technique (7) is used to determine the residual stress state in the samples. In the holographic-hole drilling method, a region of a test object containing stress is illuminated with laser light using an optical setup. A hologram of the region is made by exposing a recording plate in a commercially available holocamera to the light of a reference beam and that of the object beam as reflected from the test object. The hologram is recorded electrostatically on an erasable, re-useable thermoplastic medium. Then a small square-bottomed hole is milled into the region of interest to a depth that can be varied, but which is generally a fraction of the hole diameter. The hole releases residual stresses locally, causing material surrounding the hole to deform in response to the stress relief. The resulting surface deformations, which are both in-plane and out-of-plane, alter the path length of the light reflected from the region, immediately creating a pattern of optical interference fringes on the hologram. The interference fringe pattern can then be analyzed to determine the residual stresses that existed prior to the introduction of the hole.

Figure 2 shows the effect of thermal history on residual stress during part fabrication at various powers and traverse velocities. Sample #2 is similar to the previous thermocouple work. In this sample, the residual stress is reasonably high near the substrate, 50 ksi or 55% of the typical yield stress (90 ksi), but this value decreases after one inch of fabrication, reaching an asymptotic value of 30 ksi at two inches. During initial fabrication (Z < 0.5"), the substrate efficiently removes the laser-generated heat from the LENS sample, resulting in a large thermal mismatch and higher residual stress state. As the substrate and the LENS part are heated due to fabrication, the thermal mismatch is reduced, and the residual stress values diminish.

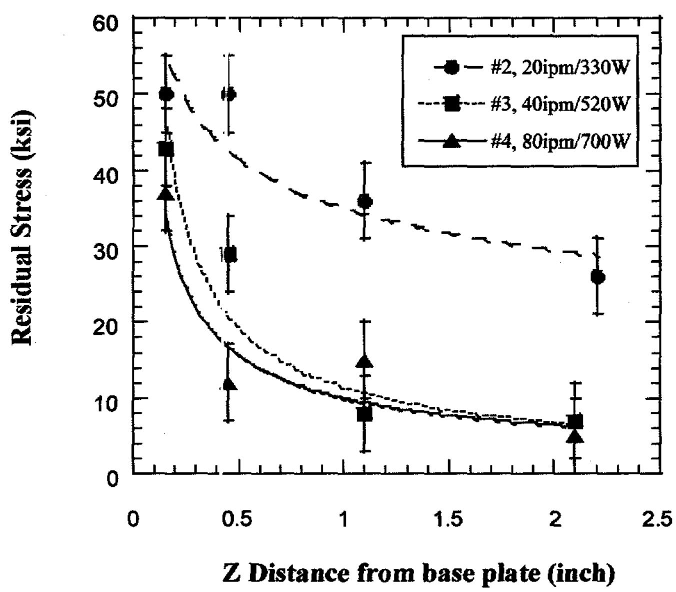


Figure 2: Effect of volumetric exposure (J/cm^3) on residual stress distribution along Z direction.

The effect of temperature on the resulting residual stress state is more apparent as the laser power is increased. Figure 2 shows the effect of volumetric exposure, ratio of power to deposition velocity, on the residual stress distribution. Nominally, the samples have the same volumetric exposure but the power, or thermal behavior, strongly influences the resulting residual stress values. At higher powers and when the thermal behavior is no longer influenced by the substrate, the values for residual stress dramatically decrease to less than 10 ksi. Moreover, the residual stress distribution could be reduced if substrate preheat was applied during processing. Therefore the large thermal mismatch at the interface would be reduced or eliminated.

Microstructural Evolution during LENS Processing

For conventional austenitic stainless steels, post-forming heat treatments are typically used to reduce residual stress while retaining the corrosion resistance of the material (8). Using LENS processing parameters similar to Samples #1 and #2, the resulting material (2) has high room temperature tensile strengths (yield = 90 ksi, ultimate = 120 ksi) with retained ductility (50%). Even though these samples receive thermal excursions around the annealing temperature for SS316 (1040 °C), which alleviate residual stress, the as-processed material does not diminish in strength. This can be attributed to the short duration of the thermal cycles, which do not overage the fine microstructural features.

In Figure 2, initial results show a correlation between laser power and residual stress. An increase in laser power leads to further annealing which lowers residual stress values. This is most likely the result of extended temperature cycles above the annealing temperature with increasing power. Currently, each sample's thermal history and its effect on microstructure and mechanical properties are under investigation.

Another important component is the nominal 'background' temperature during part fabrication, and its contribution to microstructural evolution and material's properties. In LENS processing, the background temperature is at least 500 °C, which can adversely effect the corrosion resistance of the material. Carbide precipitation and coarsening can occur between 425 and 900 °C, and microstructural investigation of the samples is underway to study this potential aging effect.

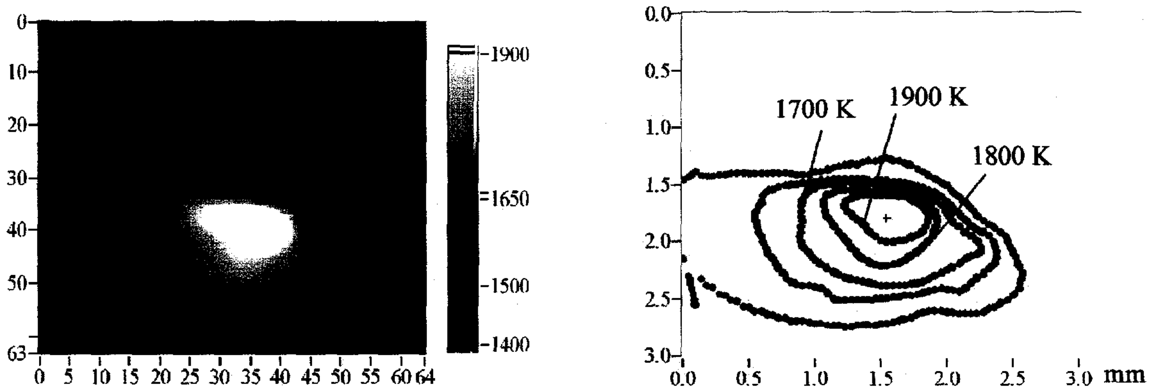
Non-invasive Thermal Imaging Techniques

As discussed earlier, it is known intuitively that a thermal gradient exists across the molten pool and into the bulk material created by the LENS process. The nature and extent of this gradient has not been fully characterized. Since mechanical properties are dependent upon the microstructure of the material, which in turn is a function of solidification and thermal history, an understanding of the temperature gradient induced by LENS processing is of special interest. It would be particularly beneficial to use non-invasive thermal imaging to measure the temperature profile and gradients and to use these thermal profiles in feedback control. Preliminary results using a high speed visible imaging technique to measure the molten pool temperature and its corresponding gradients will be shown. Studies using an infrared camera system to measure far field, part geometry thermal gradients is another useful technology under investigation and results have been discussed elsewhere (1). With these two techniques, it is possible to obtain a complete picture of the thermal behavior, near and far from the molten pool, during LENS processing.

High Speed Visible Imaging

Preliminary experiments were conducted using ultra high speed digital imaging techniques (1, 9) during LENS processing to provide insight as to the size of the molten pool and the thermal gradient in 316 stainless steel (SS316) samples fabricated using the LENS process. Digital images were obtained directly through a CaF_2 viewport in the LENS glovebox using a 12 bit digital camera equipped with a telephoto lens and 650nm broad band filter. A total of 2048 frames/run were recorded at a rate of 1.4 ms/frame. Temperatures were obtained using standard pyrometric techniques. The results shown are for SS316 material built at a nominal laser power of 275W. A single, one line width wide wall was fabricated with 0.010" layer increments, where the traverse direction is from left to right.

Figure 3(a) is a digital image of the moving molten pool and the adjacent bulk material created during processing. The field of view encompasses approximately 5 mm, where the top layer is being deposited on the previous layer with a curved profile in the region of the molten pool. Figure 3(b) shows the temperature contours of the molten pool, where the material solidifies at approximately 1700 K. From Fig. 3(b), the pool length is around 1.2 mm (or 0.047 in). It is also apparent in Figures 3(a) and 3(b), the previous layer is substantially reheated, and in fact, a good fraction of the previous layer is remelted to fuse the layers together.



(a) (b)

Figure 3: (a) Digital image of molten pool and bulk material during LENS processing of SS316 and (b) the temperature contours of the molten pool.

Figure 3 shows that the molten pool reaches temperatures on the order of 1975 K (reasonably large superheat) with a linear decrease in temperature until thermal arrest (solidification) occurs at approximately 1700 K. Upon solidification, bulk material continues to cool similar to the thermocouple measurements. In Figure 3(b), the gradient at the center of the molten pool is zero (indicated by + symbol), where immediately adjacent (~0.25 mm), the solidification rate is 3000 K/s. A maximum rate of 4000 K/s is indicated in the region approximately 0.5 mm from the molten pool. The gradient decreases sharply with distance from the molten pool until solidification occurs, at which point the rate levels out to approximately 500–600 K/s. These values around the molten pool are high enough to explain the high strengths obtained during LENS processing.

This work shows that visible imaging techniques can easily measure the fine change in temperatures around the molten pool, and further work is required to monitor the various thermal signatures, including superheat and the thermal gradients.

Conclusions

Thermal measurements are a powerful tool to understand processing conditions and their effect on subsequent material properties. Our initial results show large thermal excursions during LENS processing. Large solidfication gradients near the weld pool are beneficial for resulting high strength properties in SS316. However, large thermal excursions in the bulk of the material during fabrication can, potentially, have mixed results. As the LENS component bulk temperature increases, there are dramatic decreases in residual stress values- a beneficial consequence. Further investigation is needed to understand the effects of bulk temperature on mechanical properties. We need to understand and manage these thermal excursions for routine, robust part fabrication.

References

1. M. L. Griffith et al., "Thermal Behavior in the LENS Process", Solid Freeform Fabrication Symposium Proceedings, August 10-12, 1998, Austin, TX, in press.

2. M. L. Griffith et al., "Freeform Fabrication of Metallic Components using Laser Engineered Net Shaping (LENS)", Solid Freeform Fabrication Symposium Proceedings, August 12-14, 1996, Austin, TX, p. 125.

3. E. Schlienger et al., "Near Net Shape Production of Metal Components using LENS", Proceedings of the Third Pacific Rim International Conference on Advanced Materials and Processing, July 12-16, 1998, Honolulu, HI.

4. M. L. Griffith et al., "Multi-Material Processing by LENS", Proceedings of the Solid Freeform Fabrication Symposium, August, 1997, Austin, TX, p. 387.

5. J. E. Smugeresky et al., "Laser Engineered Net Shaping (LENS™) Process: Optimization of Surface Finish and Microstructural Properties", Proceedings of the World Congress on Powder Metallurgy and Particulate Materials, June, 1997, Chicago, IL.

6. M. L. Griffith et al., "Using Laser Engineered Net Shaping (LENS) to Fabricate Metal Parts", Proceedings of the Rapid Prototyping and Manufacturing Conference '97, April 22-24, 1997, Dearborn, MI.

7. A. Makino, D. V. Nelson, E. A Fuchs, and D. R. Williams, "Determination of Biaxial Residual Stresses by Holographic-Hole Drilling Technique", J. of Engineering Materials and Technology, Vol. 118, 1996, p. 583.

8. Davis, J. R., ed., ASM Specialty Handbook, Stainless Steels, (Materials Park, OH: ASM International, 1996), 290.

9. W. H. Hofmeister, R. J. Bayuzick, and M. B. Robinson, "Noncontact Temperature Measurement of a Falling Drop", International Journal of Thermophysics, Vol. 10, No. 1, p. 279-292.