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IMPACT OF DIRECTED ENERGY DEPOSITION PARAMETERS ON MECHANICAL DISTORTION OF LASER DEPOSITED TI-6AL-4V

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Abstract

The effects of laser-based powder-fed directed energy deposition processing parameters on the distortion of deposited Ti-6Al-4V parts are assessed through in situ monitoring. Experiments were conducted wherein substrate thickness, deposition thickness, and initial substrate temperature were varied in order to investigate their effects on distortion. Correlations of process parameters to the mechanical characteristic were also developed, uncovering some of the driving mechanisms of the measured characteristic. This work highlights the impact of substrate preheating on distortion. Most notably, the effect of initial substrate temperature on distortion depended on the size of the substrate. On thin substrates, preheating reduced the total amount of distortion. However on thick substrates, preheating increased the amount of distortion. Techniques to mitigate the unwanted mechanical defect are discussed.

Keywords: Directed energy deposition; Laser cladding; Ti-6Al-4V; Additive manufacturing; Distortion; In situ measurements

Introduction/Background

Directed-Energy-Deposition (DED) is an Additive Manufacturing (AM) process that can be utilized for the repair of worn, corroded, or damaged high-value, engineered, metal components through layer-by-layer depositions involving the injection of metal powder into a melt pool formed by a laser beam. DED provides a low-distortion repair alternative to conventional arc weld repairs for worn or damaged parts, and can be used to apply coatings with improved surface properties.

The correct combination of machine process parameters is required to create a successful deposit, as defined by criteria related to the quality of the final build. A key criterion is the dimensional accuracy of the final part, which is affected by the temperature distribution throughout the build [1]. Unfortunately, the process of developing parameters that yield low distortion can be a time-consuming trial-and-error process. Therefore, it is essential to understand how the variation of process parameters affects distortion.

Previous studies have investigated experimental techniques to correlate deposition process parameters to final distortion. Using strain gauges and computer numeric control (CNC) measurement techniques, Klingbeil et al. measured post-process substrate surface strains and final residual stress induced distortion that resulted from direct metal depositions of 308 stainless steel [2]. Klingbeil et al. varied substrate preheating (manually preheated using a welding torch) and deposition path, finding that preheating substrates reduces substrate warping, and that deposition paths that take advantage of inherent substrate preheating reduce warping. Jendrezejewski et al. studied the effects of base preheating on the strain-stress fields of stellite SF6 coating on X10Cr13 chromium steel, finding that preheating reduced the amount of bending and preheating at temperatures around 500°C produced crack-free coatings [3]. Deo and Michaleris studied the effect of preheating a weld region before deposition finding that preheating has the potential to achieve zero net distortion [4]. These studies, however insightful to the results of parameter selection on substrate distortion, do not provide insight into the real time accumulation of distortion through the process. This information can only be achieved through study of in situ measurements of distortion.

Within the last decade, numerous in situ measurement techniques have been used. Plati el al. used a linear variable differential transducer (LVDT) at the free end of a cantilevered 304 stainless steel substrate to measure the bending of the substrate at a single point during the deposition of metal matrix composite (MMC) powder [5]. Ocelik et al. used 3D digital image correlation photogrammetry for in situ measurement of multiple modes of distortion of steel substrates [6]. Lundbäck and Lindgren used 3D optical deformation analysis during a gas tungsten arc welding process [7].

More recently studies have used laser displacement sensors (LDS) to measure substrate distortion throughout the deposition process. Denlinger et al. explored the effect interlayer dwell time has on the accumulation of distortion [8], finding that the addition of a dwell time increased the amount of distortion during the deposition of Ti-6Al-4V powder, but decreased the amount of distortion during the deposition of Inconel® 625 alloy powder. Heigel et al. investigated the effects that laser power, travel speed, and deposition patterns had on substrate distortion [9], testing longitudinal and transverse deposition patterns and found that longitudinal deposition patterns created constant accumulation of distortion with time while transverse deposition patterns produced inconsistent accumulation of distortion with time.

In this study, substrate thickness, deposition thickness, and initial substrate temperature were varied between depositions of a small patch representing a possible repair procedure. The effects of the variation of substrate preheating were investigated and reported in regards to the effects they had on distortion for both thin and thick substrates. The goal of this work was to identify the mechanisms in directed energy deposition processes that cause distortion.

Methodology

Experimental setup

For this study, an Optomec LENS MR-7 machine — a laser-based, DED system with a 500 W IPG Yb-doped fiber laser — was used to deposit a 25.4 x 25.4 mm patch of various thicknesses of Ti-6Al-4V powder onto 76.2 x 50.8 mm (thicknesses of 2.54 or 12.7 mm) substrates of the same composition. To prevent oxidation during processing, the chamber of the machine was filled with argon, maintaining an oxygen content below 20 ppm, measured using an electrochemical sensor. During deposition, four radially-symmetrical nozzles injected Ti-6Al-4V powder at a rate of 2 g/min into the melt pool. The powder used was produced by the Plasma Rotating Electrode Process (PREP®) process, then sieved to a -100/+325 sieve range (which corresponds to powder diameters between 44 µm and 149 µm). Additionally, a nozzle coaxial to the laser beam directed an argon jet to shield the focusing optics from process contaminants.

Substrates were clamped into a double-cantilevered fixture, below which was a laser displacement sensor as, seen in Figure 1. This cantilevered clamping configuration limited out-of-plane distortion and represented a large-area repair. The fixture was arranged so that the substrates were 9.27 mm below the powder feeding nozzles, as shown in Figure 2. At the substrate surface, the second-moment laser beam diameter was 0.99 mm, as measured by a PRIMES® Focus Monitor system and the powder distribution focus was below the substrate surface. During deposition, the fixture moved in the x-y direction beneath the laser via a two-axis, x-y stage, while a one-axis, z stage moved the laser processing head vertically between layers.

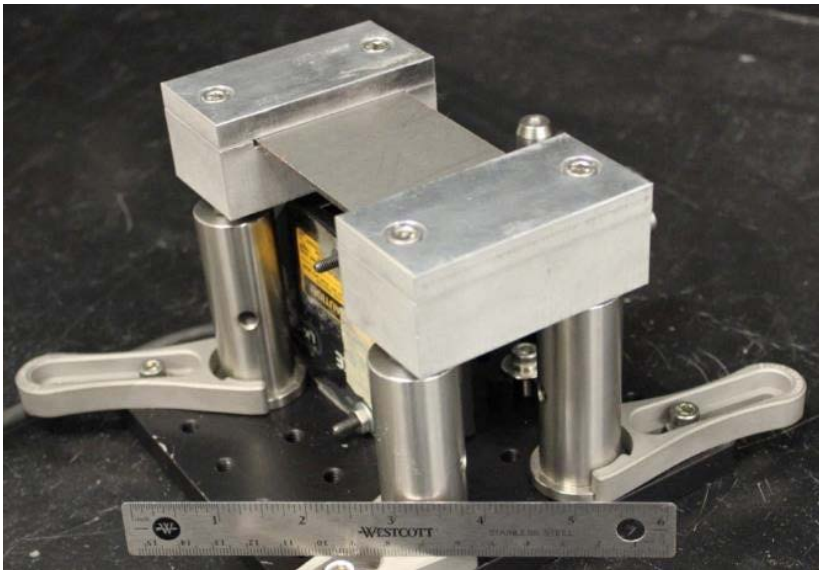

Figure 1 Fixture used to clamp substrates

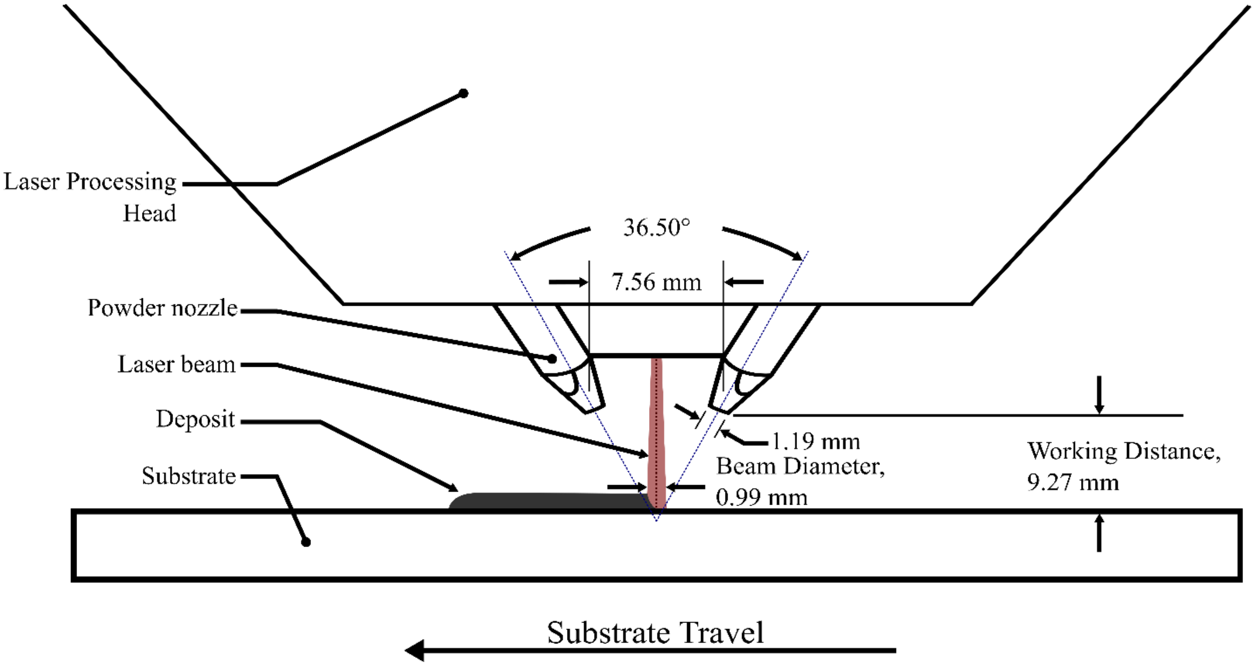

Figure 2 Schematic of substrate beneath laser head

Process parameters

To assess their influence on deposit distortion, substrate thickness, deposition thickness, and initial substrate temperature, respectively, with all other process parameters held constant, were varied. Each of these parameters was varied between two levels, determined through preliminary testing to produce sound depositions (Table 1). This paper focuses on influence of initial substrate temperature on depositions atop thin and thick substrates.

Table 1 Levels of the varied process parameters

Parameters	Levels	
Substrate Thickness	2.54 mm	12.7 mm
Deposition Thickness	0.76 mm	2.54 mm
Initial Substrate Temperature	~25°C	~400°C

Table 2 Constant process parameters

Laser Power [W]	Travel Speed [mm/s]	Powder Flow Rate [g/min]	Hatch Spacing [mm]	Layer Height [mm]
300	10.58	2	0.714	0.254

Two different substrate thicknesses were used to adjust the flexural rigidity of the substrate (Figure 3a and Figure 3b). Deposition thickness was varied by modifying the number of deposited layers. To vary initial substrate temperature, substrates were preheated using a custom-made block heater. The heater was fabricated from a 12.7 mm thick block of steel with two evenly spaced 3/8” holes drilled through the side for heating cartridges to fit into. One 3/8” hole was drilled down through the center of the top surface for a thermocouple probe. An Omega® CNI8DH temperature controller was used to monitor the thermocouple probe and control the heater temperature to a set value of 400°C. The assembly was placed on top of the substrate such that the steel block was flush against the substrate and the probe touched only the surface of the substrate. The setup is schematically represented in Figure 4. During deposition, each patch was produced using the processing parameters shown in Table 2. A zig-zag, parallel hatching strategy was used, as illustrated in Figure 5.

Figure 3 Schematic of the combination of substrate thicknesses and deposit heights

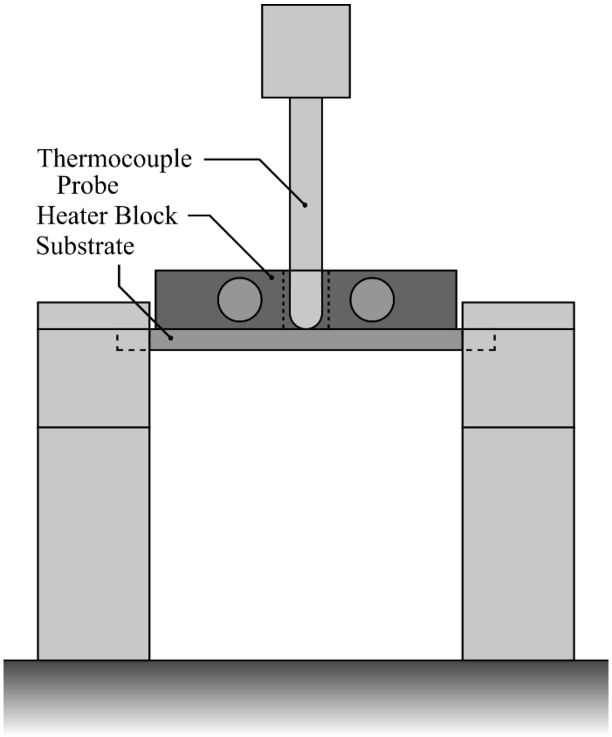

Figure 4 Schematic of heater placement on substrate

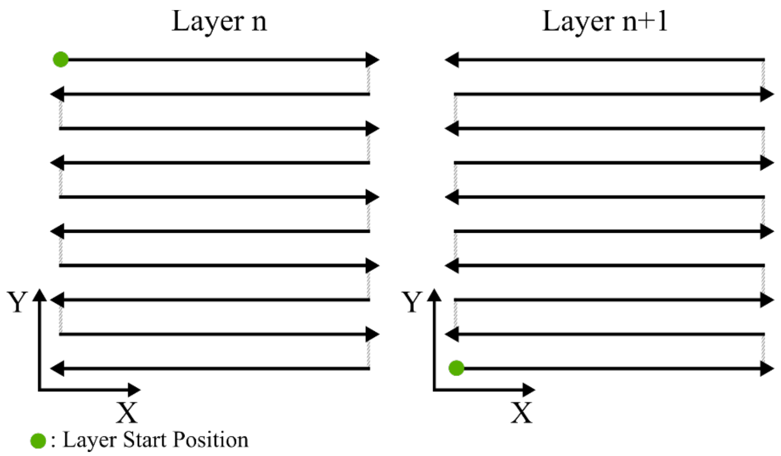

Figure 5 Parallel hatching used for patch build-up.

Data collection

During deposition, the substrate distortion was measured and recorded using a Keyence LK-031 LDS positioned directly beneath the substrate. The sensor measured and recorded the bending distortion of the substrate during deposition with a resolution of 1 μm and linear accuracy of ±1 μm. Distortion data was recorded at 20 Hz starting from the beginning of the deposition process, through the completion of deposition, and until the substrate surface cooled to 60°C to measure the full range of distortion.

Omega GG-K-30 type K thermocouples laser welded to the top surface of the substrate at various locations were used to measure location-specific temperature history of the substrate during deposition. These thermocouples recorded temperature history at a rate of 60 Hz with a measurement uncertainty of 2.2°C or 0.75%. Temperature measurements were recorded synchronously with the timestamp, position of the laser head, and distortion measurements. The locations of the welded thermocouples on the surface of the substrate along with the location of the LDS measurement are illustrated in the schematic in Figure 6.

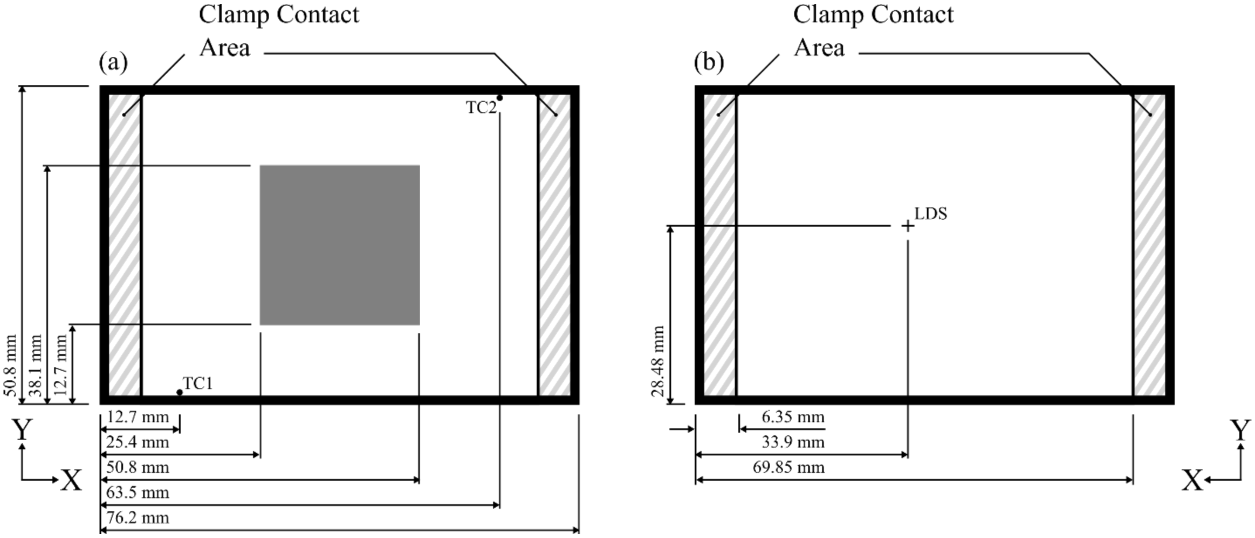

Figure 6 Schematic of the top (a) and bottom (b) of the substrate illustrating the location of the measurement sensors

After deposition, the patch height was measured on from each run to ensure proper build size. The height was measured at the center of the patch using digital calipers.

Results and Discussion

Adjustments of processing parameters resulted in variations in in-situ measurements of thermal deformation. The effects of substrate preheating on distortion were analyzed by isolating the change in preheat between the results of four separate runs and comparing the corresponding in situ distortion measurements.

The results showed that preheating of a substrate before deposition had an impact on the amount of total distortion and the rate of distortion. When preheating a thin substrate (2.54 mm thick), the amount of distortion decreased by 22.1%, from 0.83 mm to 0.65 mm, relative to the room-temperature case (Figure 7 (left)). By the end of the first layer, the effect of preheating had already decreased distortion by 0.20 mm (33.3%), and by the end of the second layer it had decreased distortion by 0.20 mm (30.4%). By the end of the third layer distortion had decreased by 0.20 mm (24.3%).

When preheating a thick substrate (12.7 mm thick), the amount of distortion was shown to increase (Figure 7 (right) and Figure 8). The final measured increase in distortion was 111.9%, relative to the room-temperature case. Distortion of the preheated case did not reach a steady-state before the end of data collection. The distortion results of the preheated 12.7 mm thick substrate also exhibited similar distortion rate during the deposition of each of the 10 layers. Most distortion occurred after deposition concluded, during cool-down.

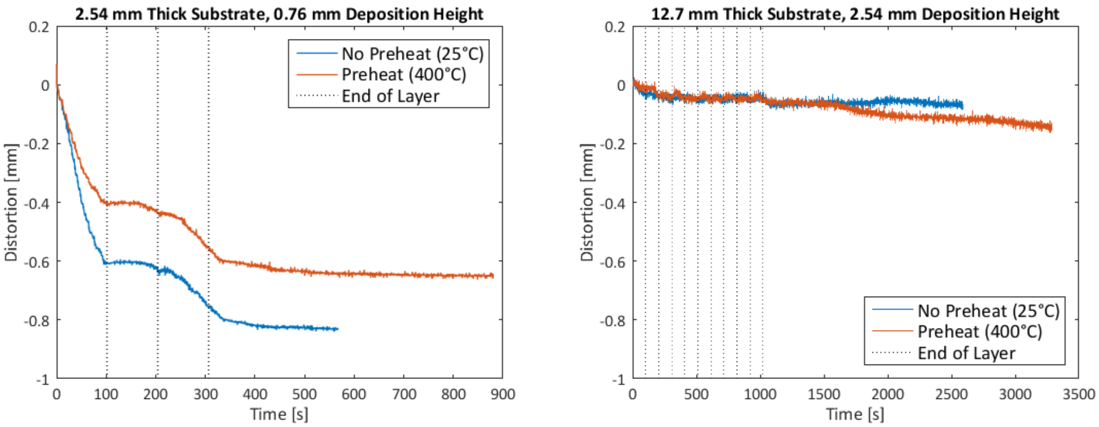

Figure 7 Effect of substrate preheating on distortion for a 0.76 mm thick deposit on a 2.54 mm thick substrate (left) and on a 2.54 mm thick deposit on a 12.7 mm thick substrate (right)

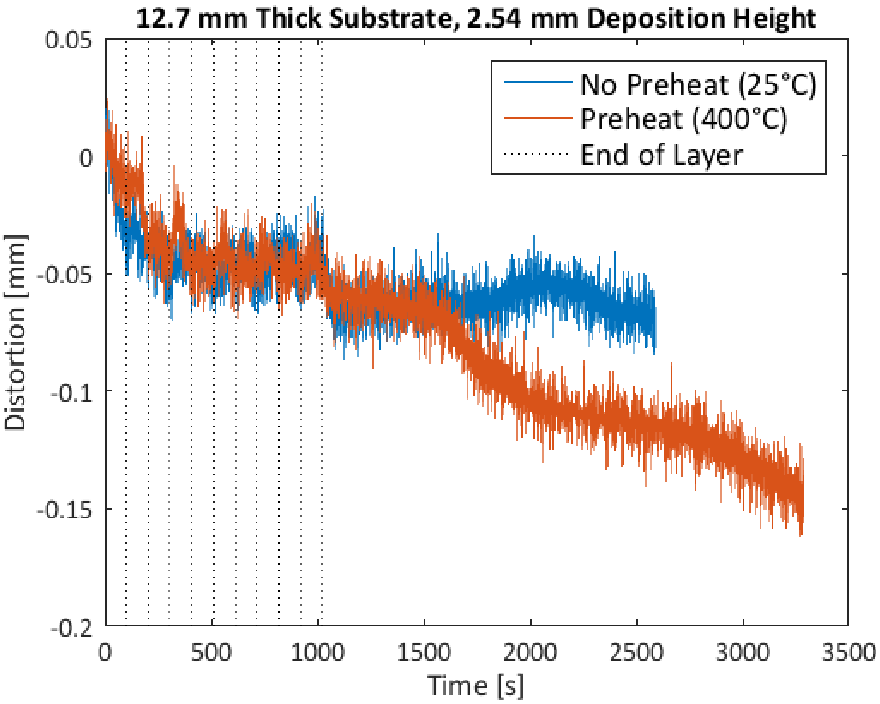

Figure 8 Effect of substrate preheating on distortion for a 2.54 mm thick deposit on a 12.7 mm thick substrate

The most notable result was that substrate preheating had differing effects on distortion depending on the thickness of the substrate. Preheating of a thin substrate decreased the amount of distortion whereas preheating a thicker substrate increased the amount of distortion. By preheating a thin substrate, the temperature difference between the substrate surface and the melt pool was reduced. In the case of the preheated substrate, the higher surface temperature will lead to a reduction in the thermal gradient, which should result in a reduction of distortion. But this effect is not observed with the thick substrates.

These counter-intuitive results could be attributed to a variety of reasons. One possible explanation could relate to the method of preheating. In this study, substrate preheating induces a localized heat source to only the top surface of the repair substrate. With this method, a thin substrate would be heated to a more uniform temperature before deposition, whereas a thick substrate would have a larger temperature difference between the top and bottom surfaces of the substrate. These temperature differences could indicate a difference in thermal gradient. The actual reasons behind the counter-intuitive effect of thick-substrate preheating are under investigation.

Conclusions

This study presented an analysis of in situ distortion data from a series of laser-deposited Ti-6Al-4V patches wherein substrate thickness and preheating were varied. It was shown that the distortion of the thin geometries can be mitigated by increasing the initial substrate temperature. However, preheating of thick substrates increased substrate distortion. The reasons for this effect are unclear and warrant further investigation. Although no quantitative analysis of the thickness of the substrate was performed, the results of this experiment suggest to avoid preheating of thicker substrates or to perform preheating on a thinner substrate to mitigate any effects of part distortion during the deposition process.

Acknowledgements

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