Beyond layer-by-layer Additive Manufacturing – Voxel-wise Directed Energy Deposition

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Abstract

Conventional additive manufacturing is a layer-by-layer process, reliant on the sequential deposition of 2-1/2 D layers oriented along a build axis. During directed energy deposition a feed-stock is directed into a continuous melt pool formed by a laser or electron beam. The ability to produce overhangs is limited due to the gravitational, surface tensions, and fluid-flow force acting on unsupported melt pools. Here, we present a novel, directed-energy-deposition technique where vertical and overhanging structures are formed by laser power modulation and the motion of a laser beam in three dimensional space along the build-up direction, rather than strictly in a single layer. We demonstrate that highly-overhanging Ti-6Al-4V structure, i.e. in which the overhang angle exceeds 45 degrees with respect to the x-y plane, can be deposited using the developed technique. High-speed imaging is used to gain insight into the physics of the process. The use of a pulsed or power-modulated beam is found to be critical to the formation of overhangs.

1. Introduction

Classically-defined, additive manufacturing (AM) encompasses a family of technologies based upon successive deposition of 2-1/2 dimensional layers. Powder bed fusion (PBF) or directed energy deposition (DED) [1] can be used for fabrication of fully-dense metal components. In the former, a layer of powder is spread across a build plate or previously-fused area followed by the exposure of a rapidly moving heat source (e.g. electron beam or laser beam). The beam melts and fuses the powder to a portion of the underlying substrate. Directed energy deposition relies upon a different mechanism for the introduction of the feed-stock material: powder can be blown using a coaxial or off-axis nozzle arrangement into a melt pool formed by a heat source (e.g. electron beam, laser beam, or torch) or wire can be directed into the melt pool using a wire feeder.

Overhanging structures—structures which do not lay entirely atop underlying, fused material—can be readily deposited using PBF processes because the surrounding powder in the bed supports overlaying material. This capability enables build-up of complex three-dimensional components. In practice, the overhang angle must not exceed a maximum overhang angle, which is dependent upon the material system and processing settings [2]. For example, a maximum overhang angle of approximately 65 degrees is suggested for EOSINT M systems [3].

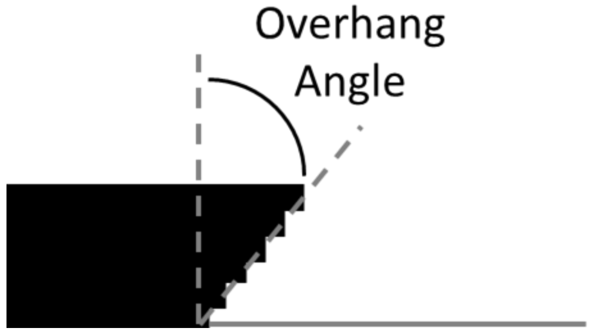

Figure 1: Overhang angle definition

The maximum overhang angle for DED is more limited than for PBF. There is a paucity of literature regarding the maximum overhanging angle possible with DED, though the deposition of overhang angles of approximate 30 degrees has been claimed [4] and a 26 degrees overhang has been reported [5] using an Optomec LENS system with a conventional 3-axis stage arrangement and deposition head. Part reorientation via tilting or rotation of the substrate or deposition head can be used to extend the overhang angle [6], [7]; however, few software tools exist for automated planning of builds utilizing four or more axes of motion. The use of robot arms may be an alternative but it's use will be limited due to low line-following accuracy [8]. Additionally, it has been reported that data-transfer requirements for control of robotic arms results in build interruptions [7].

Here, a method for deposition of highly-overhanging structures is developed. Unlike conventional additive manufacturing, the method does not rely on sequential deposition of 2-1/2 dimensional layers; rather, voxels are sequentially deposited along a vector in the desired overhang direction. Deposition of overhanging structures with angles between 0^o and 60^o (as defined in Figure 1) are demonstrated.

2. Experimental Setup

ASTM grade 5 titanium (Ti-6Al-4V) was used for both the substrate and feedstock powder. The powder was spherical, Extra Low Interstitials (ELI)-grade with a (-100+325) mesh size (44 to 149 μm). A directed-energy deposition, laser-based, Optomec, Inc. LENS MR-7 system was used for deposition. The system utilized a 500 watt, Ytterbium-doped fiber laser with a second-moment beam spot size, measured using a Primes, GmbH FocusMonitor system, of 1.24 mm at the working distance. As shown in Figure 2, the working distance corresponded to a distance of 9.27 mm between the substrate and four, radially-symmetrically powder-delivery nozzles. Centered among the powder nozzles was a coaxial, center-purge nozzle, though which 30 lpm of argon flowed.

During deposition, the processing chamber held an argon atmosphere at a gauge pressure between 2 and 3 inches of water (498-996 Pa), with oxygen concentration held below 20 parts per million. Argon gas was also used to assist the flow of powder through powder-delivery nozzles. Powder flow was measured and maintained at 3 grams per minute.

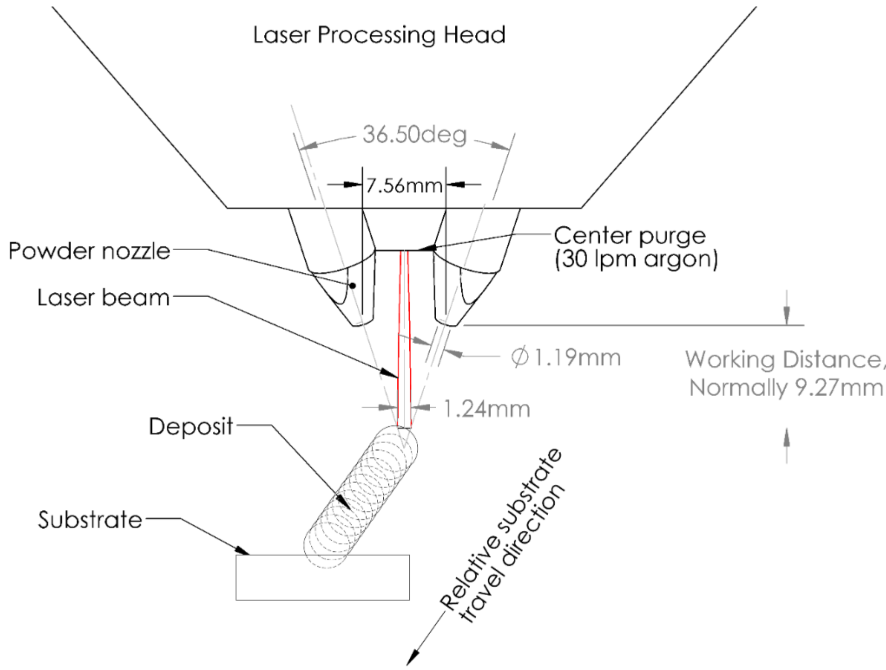

Figure 2: Laser deposition arrangement

Overhanging structures were formed by the translation of the substrate along a vector relative to the laser processing head. During translation, the laser power was modulated to produce a square wave with a peak power of 450 W, a period of 100 ms, and a 50% duty cycle. Unless otherwise stated, all deposits were formed at a constant vector translation speed of 0.42 mm/s (1 in/min) along a vector in a plane containing the laser propagation (build-up) direction. Vector was oriented at angles between 0 and 60 degrees with respect to gravity.

During deposition, high-speed video was recorded using a Vision Research Inc.V1610 Phantom High Speed camera. The camera captured 1000 frames per second with an exposure time of 100 μs. The camera was positioned outside the chamber, and viewed the process through standard laser-safe glass. A 200 mm focal-length lens was used with an F-stop of 32.

Deposited samples were sectioned, ground, and polished according to standard metallographic techniques. Samples were etched using Kroll's reagent prior to imaging.

3. Results and Data Analysis

Overhanging structures were successfully deposited between 30 and 90 degrees with respect the horizontal (x) axis. The deposited structures are shown in Figure 3. Overhanging deposit lengths as long as 50.8 mm (2 in) were deposited. A 50.8 mm long deposit with an overhang angle of 45 degrees is shown in Figure 4.

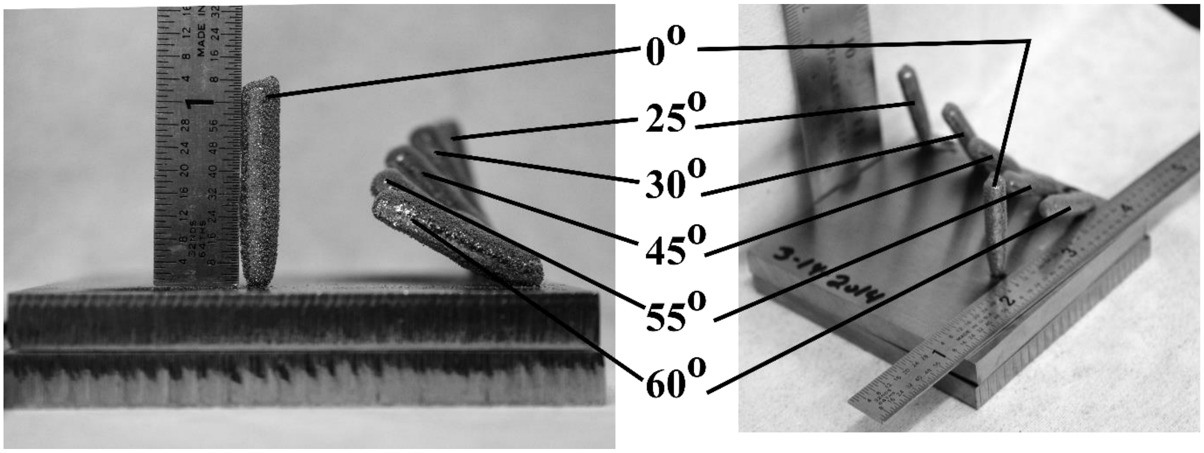

Figure 3: Overhanging structures deposited via voxel-wise deposition

Several characteristic features of the overhanging deposits are visible in Figure 3 and Figure 4: Near the substrate, the diameter of the deposit is approximately half of the steady-state deposit width. The steady-state deposit diameters, approximately 5 mm in all cases, was more than four times greater than the beam spot size. The downward-facing surface appeared smoother than the upward-facing surface

Metallographic examination revealed the formation of columnar prior beta grains oriented along the overhang build-up direction, rather than vertically with respect to gravity as typically found in layer-by-layer builds. As in other AM techniques, the prior-beta grains appear to have grown epitaxially starting from previously deposited material [9]. Within the prior-beta grains, a fine basketweave alpha-beta microstructure was observed. This is similar to other AM-deposited Ti-6Al-4V microstructures.

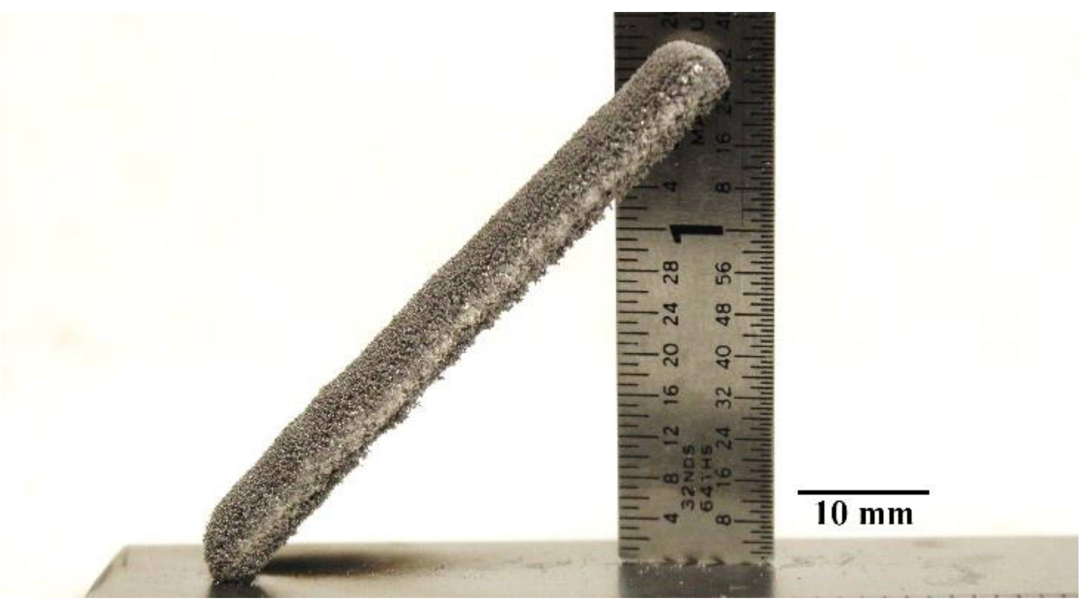

Figure 4: Forty-five degree overhanging structure.

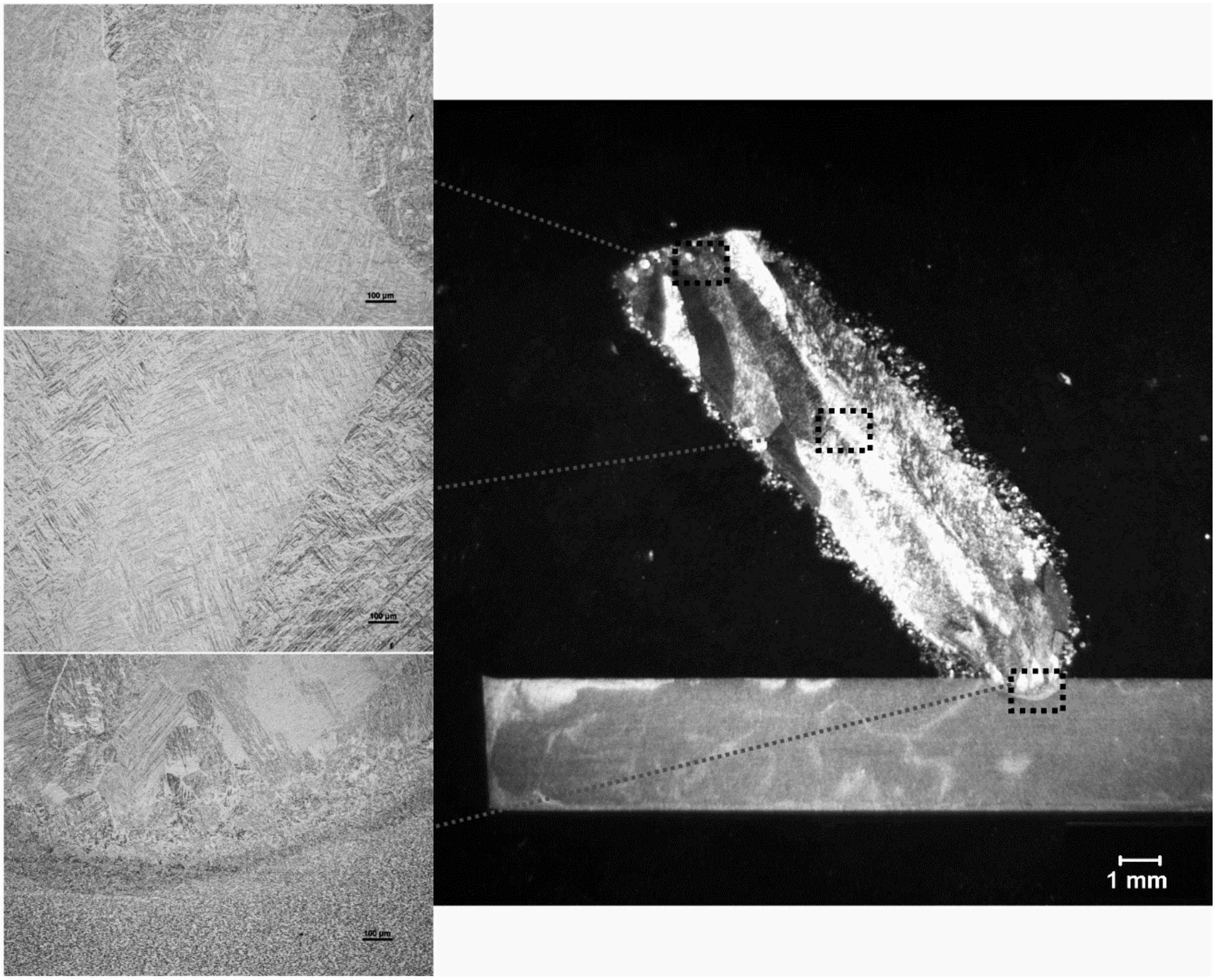

Figure 5: Micrographs and macrograph of a Forty-five degree overhanging structure.

High-speed imaging provided insight into the process by which the overhanging structures were formed. High-speed images captured at the beginning of the process during the initial deposition onto the substrate are shown in Figure 6. With respect to the axes shown in the figure, the structure was built up along the y-z plane toward the camera. At the beginning of the deposition, during the first pulse period, a semi-spherical melt pool formed. Within 10 ms, a hemispherical deposit was observed extending from the substrate. The build continued to grow throughout the laser-on cycle. Accompanying the deposition process was a metal-vapor plume. The plume maintained a parabolic shape, but fluctuated in length, width, and angle of emergence.

The laser-off cycle resulted in rapid cooling of the melt. Based on close-up examination of flow within the melt pool, it was estimated that full solidification of the first voxel occurred within 25 ms of the laser beam turning off.

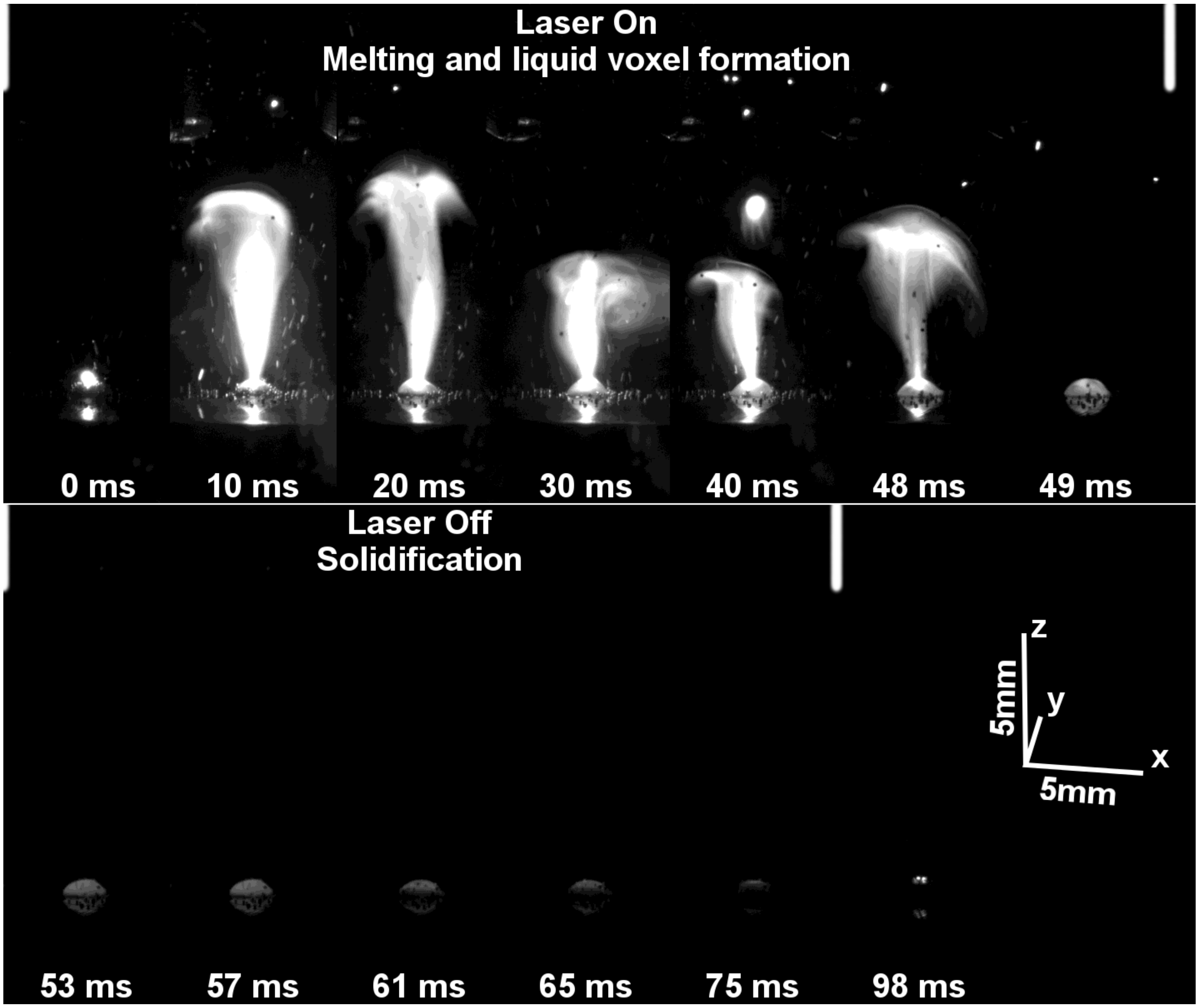

Figure 6: High speed images of the first lase-pulse period during deposition of a 45 degree overhanging structure. At the bottom of each frame, the frame time is displayed.

Solidification during the laser-off cycle is critical to the formation of the highly-overhanging structures. The results of an attempt to build a 45 degree overhanging structure using a continuous (CW) laser beam power of 450 W, with all other variables equal, shown in Figure 8, illustrates the importance of a solidification cycle.

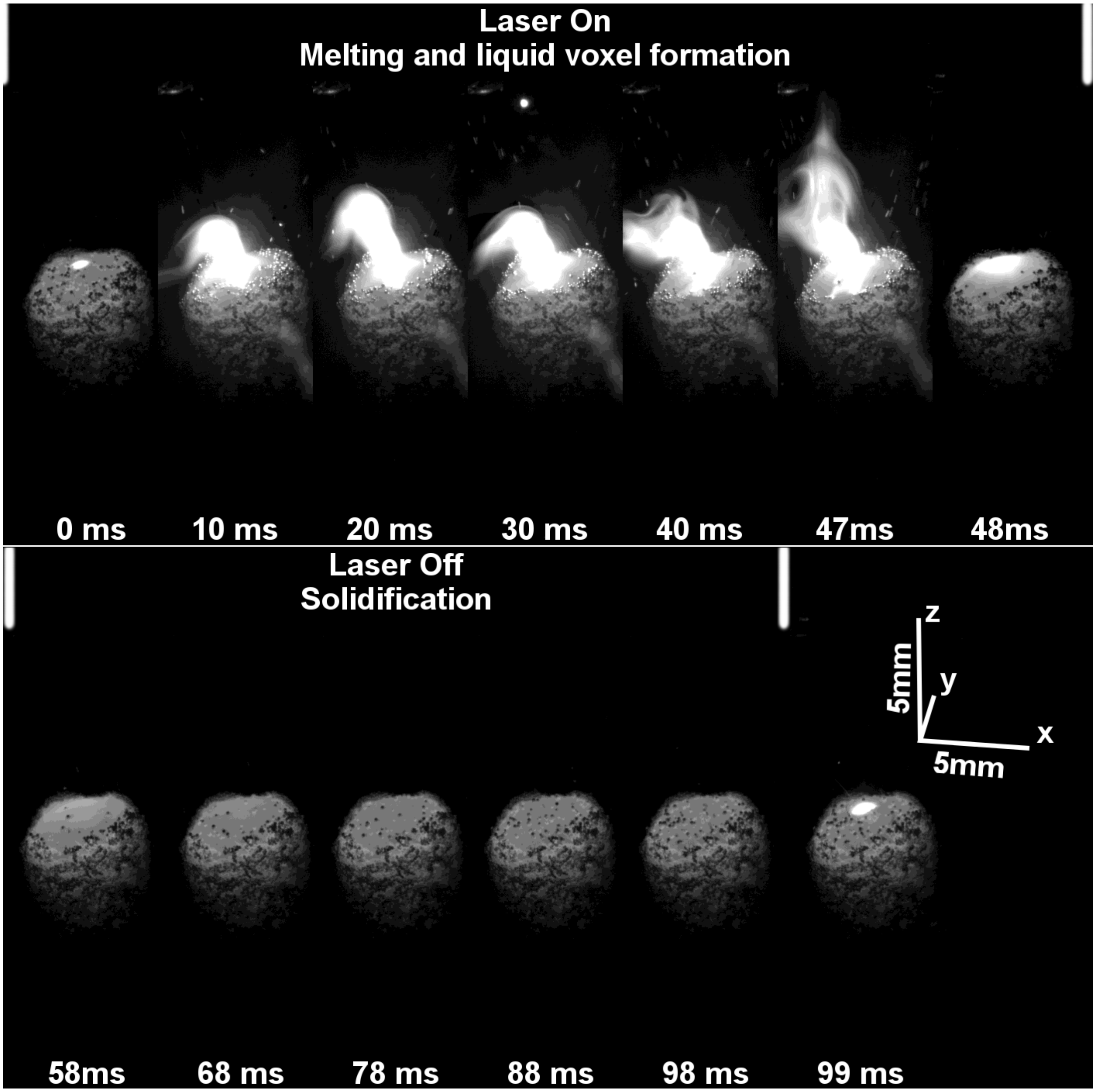

Figure 7: High speed images of a laser pulse part-way (26.3 seconds) through the build. At the bottom of each frame, the frame time, with respect to the laser-on trigger, is displayed.

Using a CW beam, an overhanging structure did not form. High-speed imaging of the CW deposition attempt over the course of 30 seconds (Figure 9) revealed the formation and continued growth of a large, melt pool held together by surface tension. The melt pool increases in size throughout the deposition process. As the deposition head moved within the y-z plane, the rear of the melt pool solidified. The melt pool solidified approximately 174 ms after the laser beam was turned off—this is determined based on observation of flow within the melt pool—leaving behind a globule laying atop the substrate.

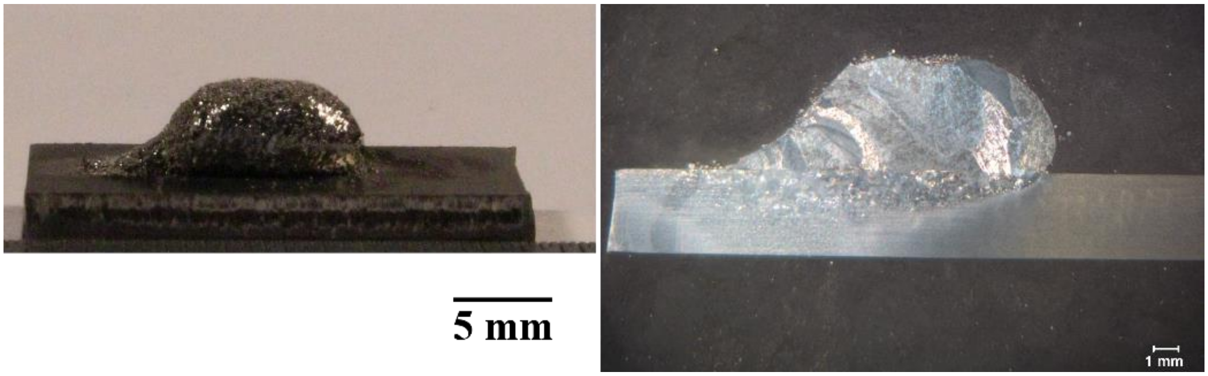

Figure 8: Attempted build-up of 45 degree overhanging structure using a CW laser beam.

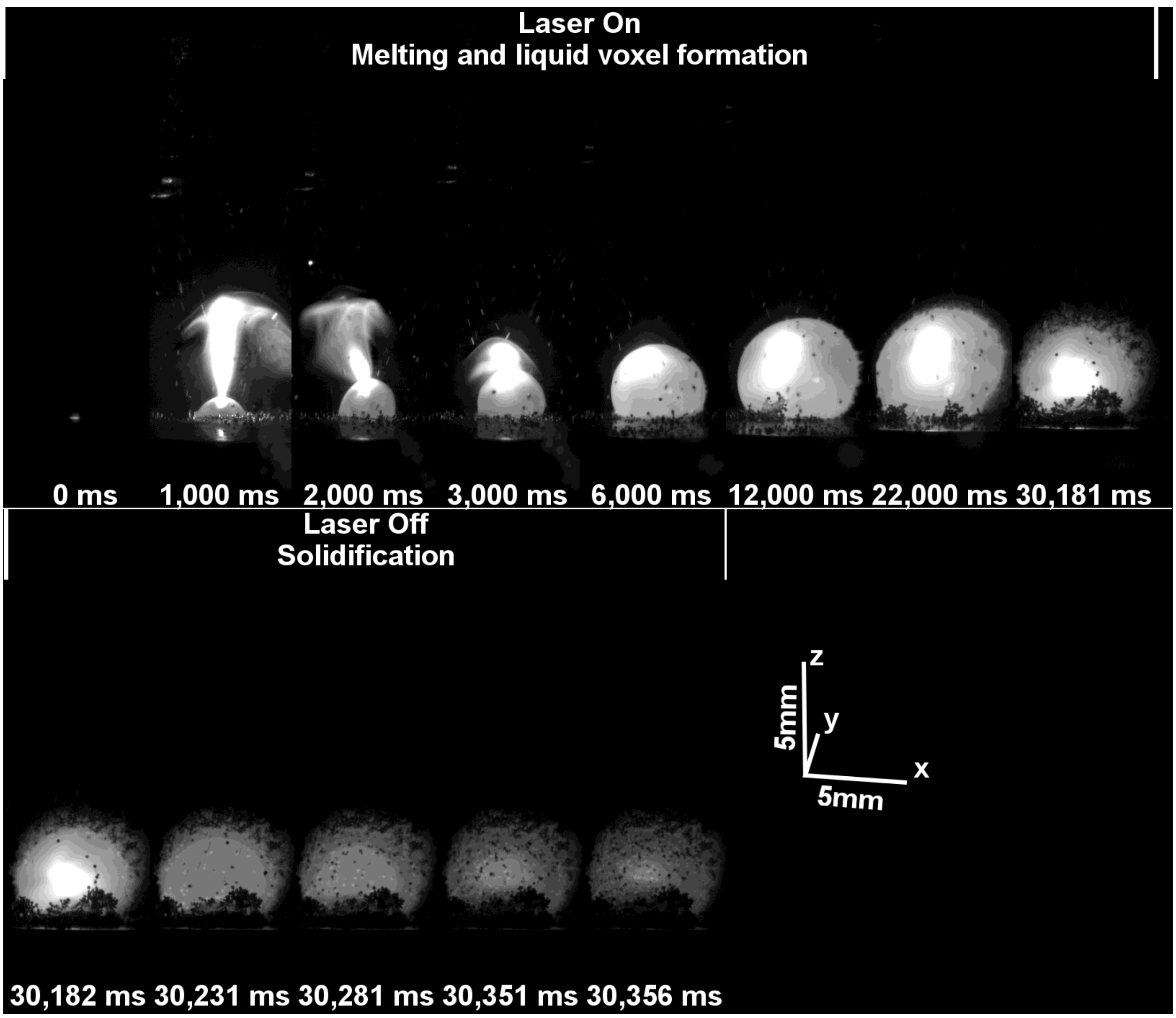

Figure 9: High-speed imaging of attempted build-up of 45 degree overhanging structure using a CW laser beam.

4. Discussion

Laser power modulation is critical to the formation of highly-overlapping structures by translation along an overhang vector. When the laser is on, a melt pool begins forming below the laser beam. This molten zone, held together by surface tension and acted upon by gravity, expands spherically while the laser beam is on. When the laser beam extinguishes, the melt rapidly solidifies—starting at the bottom and sides of the pool. The process repeats as the focal position of the powder and the laser spot translate along an overhang vector. Thus, the formation of overhanging structures is aided by two physical phenomena: surface tension coaxes the pool to form a spherical shape; and, the solidification of the melt pool exterior acts like a vessel for the solidifying voxel.

The formation of highly-overhanging structures is not possible with a CW laser beam. Continued heating of the melt pool results in the formation of large spherical melts, held together by surface tension. Without solidification of the sides of the melt, the upward build-up becomes impossible. Critical to the process is tuning of the upward motion of the stage and the laser pulse parameters: upward motion at a rate exceeding the spherical growth of the melt will lead to failure. Upward motion at a rate less than the special growth of the melt will result in a loss of process efficiency and poor geometric conformity. Within this limit, tuning of the processing parameters allows for variation in the diameter of the overhanging structures

5. Concluding Remarks

The presented method for the formation of highly-overhanging structures is a significant advancement for directed-energy deposition processes. Key to the process is the pulsing of the laser beam to allow solidification of partially-underlying voxels. However, complete solidification of an underlying voxel is not a requirement; solidification of the voxel walls are sufficient to prevent collapse of the melt pool. Given this, alternative arrangements, where beam spot size, intensity distribution, power, or powder flowrate is modulated, may be capable of producing similar results.

The process may be extended to build-up of fully-dense, three-dimensional structures, such as the simple structure illustrated in Figure 10, as well as the formation of supports. Further development of the process, together with numerical modeling, and the development of process and path planning software, may result in the ability to deposit complex, three-dimensional structures that are currently only feasible with powder-bed fusion technology, five-axis motion system, and robotic arms. Another key application of the voxel-wise deposition may be in the deposition of large, cellular structures, such as that illustrated in Figure 10.

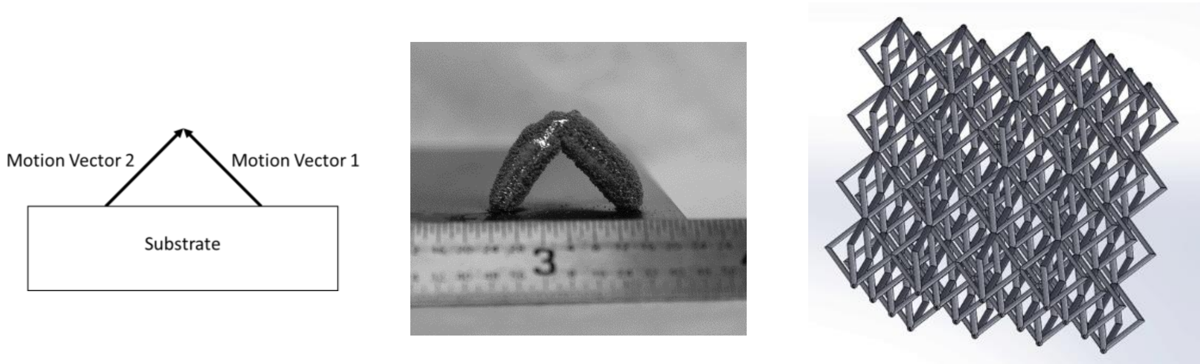

Figure 10: (left) Illustration of motion paths for the deposition (middle) of a simple three-dimensional structure using voxel-wise deposition. (right) Illustration of a cellular structure which may be deposited using voxel-wise deposition.

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