Title

A New Way of 3D Printing: Site-Specific Process-Parameter Modifications via Closed-Loop Control for Enabling Dynamic Bead Geometries and the Embossing Effect

Contributors

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Problem Statement

Conventional operation of metal additive manufacturing (AM) systems, particularly Directed Energy Deposition (DED) style systems, is for a print head to follow a designated tool path while feedstock and energy are applied in prescribed amounts that are pre-determined and very often of constant magnitude. Sometimes sensors and real-time closed-loop control systems are used to modulate process parameters, for example laser power, to control some characteristic of the process, for example melt pool size, however the goal has typically been, according to the metal AM literature, to maintain a constant, nominal value of the characteristic throughout the printing of a 3D part. The issue of local, or site-specific control, which would be driven by additional information attached to the toolpath, is of great interest to metal AM researchers. This would create the possibility of inducing site-specific, or local, bead or part geometry modifications and varying magnitudes of energy input for functionally grading component material properties. A capability of this nature would have object-security implications and enable users to emboss secondary geometry on the primary part geometry, for example a label, number, or QR code for component tracking, manage local bead consolidation to prevent the propagation of problematic volumetric defects, and intentionally vary heat input to manipulate solidification dynamics and the resulting microstructure and mechanical properties to tailor a 3D printed component for the demands of its applications.

The solution proposed, for which a case-study has been completed, is site-specific process-parameter modifications via closed-loop control in metal AM. This solution involves making site-specific modifications to a real-time, closed-loop melt pool size controller's set-point based on user input, i.e. instead of having a constant melt pool size set-point, which is the state-of-the art in the literature (the type of controller described uses a thermal camera to image the molten pool of metal, measure its size, and a software-based controller automatically

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adjusts laser power to achieve the desired size). The experimental case-study showed that through this method, it is actually possible to 3D print specific geometry that is not part of the print head's toolpath; this is believed to be a novel concept. The working terminology for this type of geometry is extra-toolpath geometry, for geometry that occurs beyond the toolpath.

Background Perspectives

There are two key aspects of this novel methodology that are used in tandem: site-specific parameter modifications and closed-loop control. The state-of-the art for closed-loop control in metal AM is to use a constant controller set-point, rather than one that varies with location [1-5]. The state-of-the-art for site-specific parameter modifications is to command open-loop changes with no sensor feedback [6]. For example, one might choose to pre-program adjustments to laser power, for example, throughout the printing of a component to attempt to replicate embossing of secondary geometry that was demonstrated in this case study. The problem with that is the magnitude of laser power that is required to achieve consistent embossing changes depending on the thermal properties of the object under construction, and it is impossible to completely predict thermal properties, which can be impacted by unforeseen print interruptions and varying levels of laser power absorption. By using closed-loop melt pool size control via manipulation of laser power, laser power automatically adjusts to achieve the desired melt pool size set-points, whether on layer 1 or layer 1000 of a print.

Technical Overview and Results of Case-Study

There are two elements of the experimental case-study presented here. The first is a side-projection of a secondary geometry for embossing, and the second is a top-down projection of a secondary geometry for defect mitigation. In the first case, the ORNL oak leaf logo was used to generate trigger points at which the melt pool size set-point would change (increase of 37.5 %) under closed-loop control in a laser-wire DED printing process. The result was that the oak leaf was embossed on an otherwise ordinary, double-bead wall printed in Ti-6Al-4V [published recently in 7]. The toolpath of the wall is shown in the slicer software environment in Figure 1. The oak leaf is not contained within the primary CAD model from which the toolpath was derived, but rather, information about the oak leaf and associated parameter modifications are embedded in the build file. While the toolpath planning method is still a vector-based approach in this example, as opposed to voxel-based, there is additional information attached to the vectors, more so than there would otherwise be in conventional printing.

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The process for utilizing the secondary geometry is shown in Figure 2. The secondary geometry for embossing is selected, it is itself sliced, and trigger points are derived from the slice which become the locations of process-parameter modifications, which in this case study were changes to the closed-loop melt pool size controller set-point. In post-printing analysis, overlaying the resulting melt pool size with the toolpath shows clearly the site-specific modifications to the melt pool size that were achieved in the print. This is shown in Figure 3. The resutling embossing magnitude that was achieved was characterized via net-shape geometrical scans carried out with a FaroArm scanner. These results are shown in Figure 4. The maximum embossing of 1.5 mm, relative to the nominal wall thickness, corresponds to 7.2% of the total wall thickness of 20.7 mm. And finally, photographs of the completed wall are shown in Figure 5, both in the as-printed and after heat treatement conditions.

In the second element of the case study, a top-down projection of a secondary geometry was used to create process-parameter modifications in order to mitigate a problematic volumetric defect that is normally present in a widely utilized cross-like toolpath in laser-wire DED. This toolpath has broad utility, especially for printing thin-walled aerospace-type part preforms. Historically, very convoluted toolpaths that are not readily generated with conventional slicing software have been used to mitigate the defect. Using site-specific control, however, simple toolpaths with additional process information attached to the beads can be used. In the case study, a cross toolpath was deposited without site-specific control as a baseline, and a cross-toolpath with process parameter modifications (increased melt pool size set-point and decreased print speed) inside a bounding box geometry was deposited as a demonstration of defect mitigation. The resulting prints, shown in Figure 6, show a stark contrast in performance and the obvious benefits and potential impact of site-specific control for defect mitigation.

Reflections

> The ability to print with dynamic bead geometries has far-reaching and impactful implications, particularly for large-scale metal AM processes like laser-wire DED, which require a different set of design rules than the majority of AM processes and has traditionally been limited to lower resolution component details.

In this case study, closed-loop, site-specific control of melt pool size was successfully utilized to impart local process changes and print an extra-toolpath geometry, i.e. a geometry that occurs beyond the toolpath. This achieved two outcomes: embossing of a secondary geometry using a side-projection technique and volumetric defect mitigation using a top-down projection technique. The ability to print with dynamic bead geometries has far-reaching and impactful implications, particularly for a large-scale metal AM process like laser-wire DED, which require a different set of design rules than the majority of AM processes and has traditionally been limited to lower resolution component details [8]. It is anticipated that the technique can be used in the near future for volumetric defect mitigation in toolpaths where local overlap of adjacent beads is inadequate. The capability to emboss specific, secondary geometry means that part identification features, such as a serial number or QR code, could be permanently added to components during the printing process. The prospect of printing single toolpath walls with varying wall widths is also attractive from a post-print machining perspective, in that, when machining thin-walled structures, pre-forms ideally contain integrated structural support such as thicker sections that buttress and support adjacent thinner sections during the machining process. Finally, an important aspect of the process demonstrated here is the closed-loop nature of the process. While it would certainly be possible to pre-program open-loop, site-specific modifications to process parameters in laser-wire DED, a closed-loop system ensures that variables, like melt pool size, are controlled regardless of the thermal properties of the component under construction.

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Figures

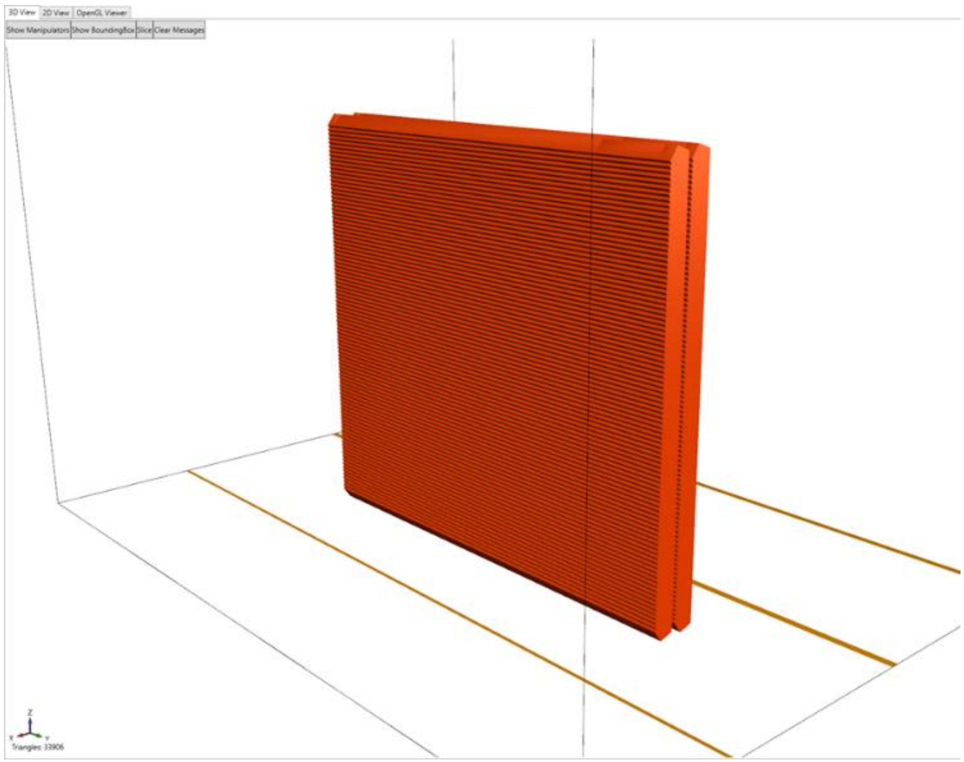

Figure 1: Toolpath for Ordinary Double-Bead Wall in the Slicing Software Environment. The Oak Leaf Geometry is not Contained within the Toolpath

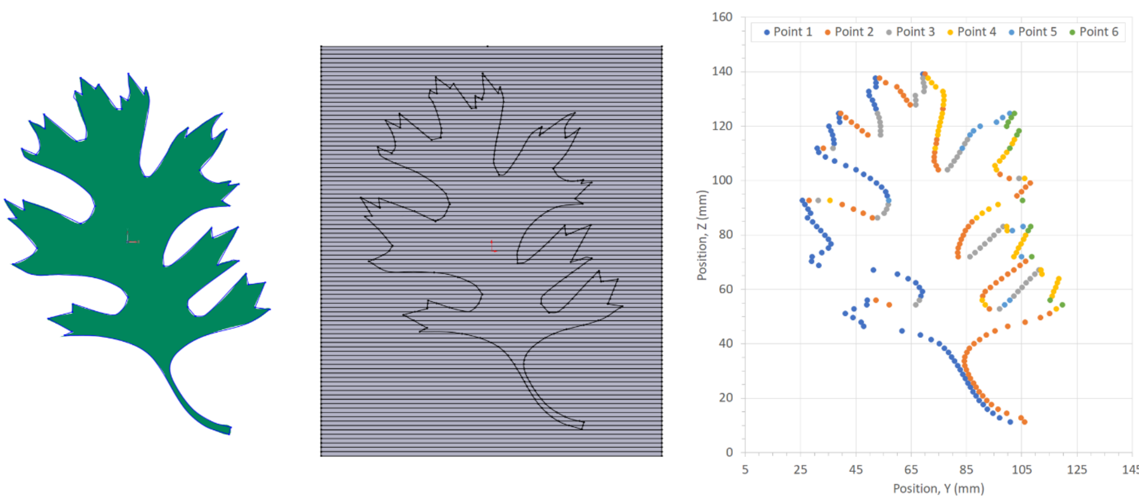

Figure 2: Process for Generating Trigger Points from the Side-Projection of a Secondary Geometry; From left to right: Geometry Selection, Slicing, Resulting Trigger Points

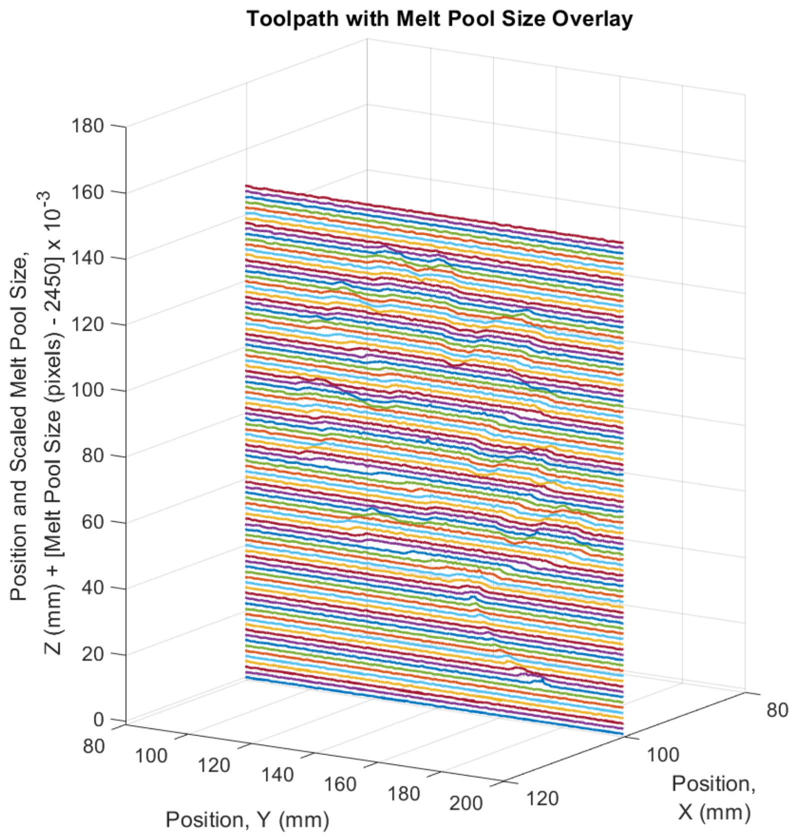

Figure 3: Toolpath with Resulting Melt Pool Size Overlay Showing the Site-Specific Parameter Modifications that were Achieved During the Print

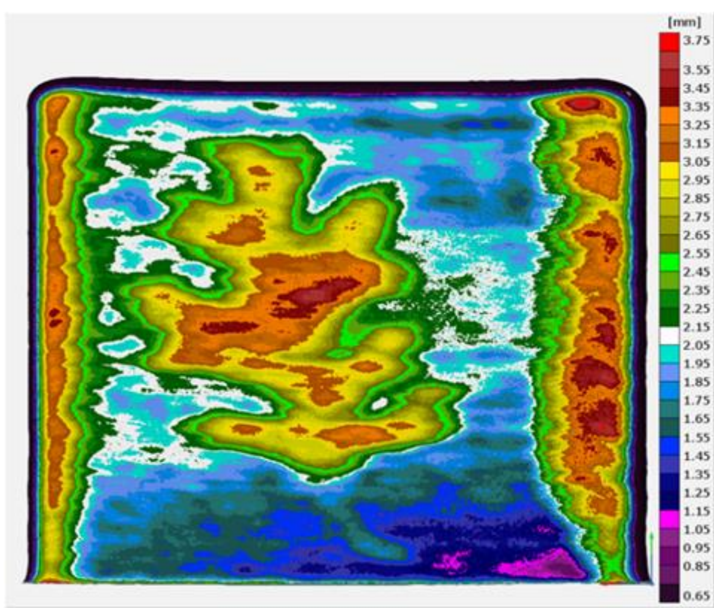

Figure 4: Embossing Magnitude of Oak Leaf, Characterized via Net-Shape Geometrical Scans Carried Out with a FaroArm Scanner; White Band is Nominal Reference Thickness

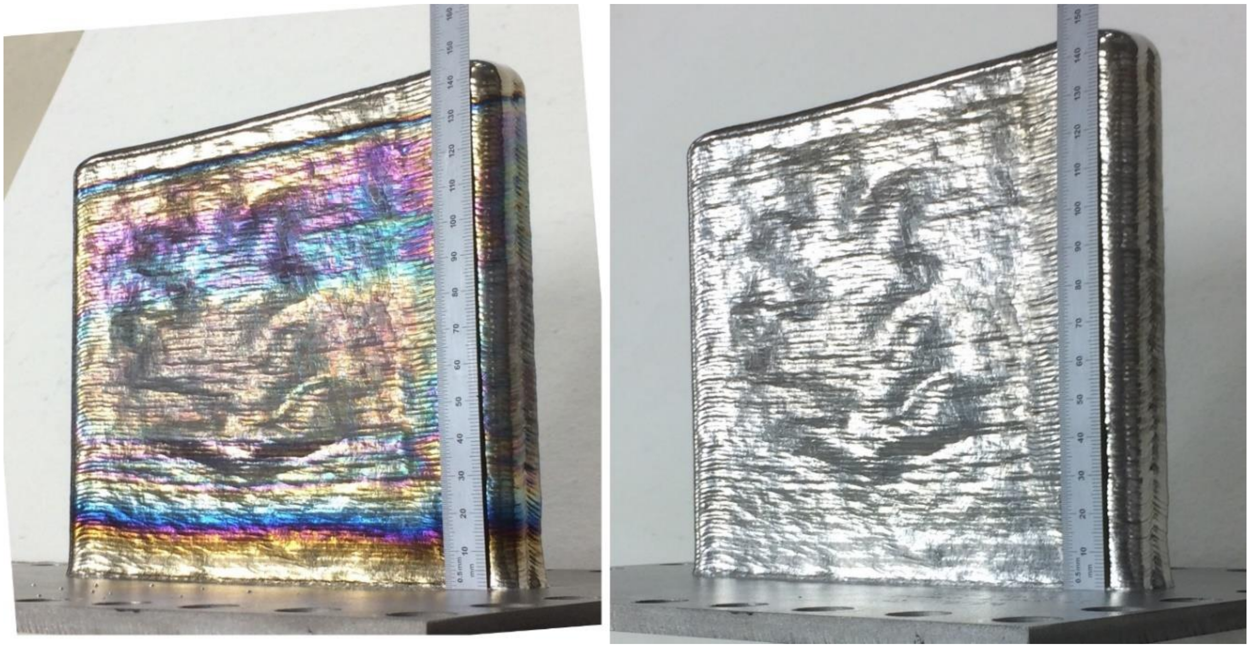

Figure 5: Case Study Wall Showing Embossed or Extra-Toolpath Oak Leaf Geometry in As-Printed Condition (left) and After Heat-Treatment (right); Material is Ti-6Al-4V

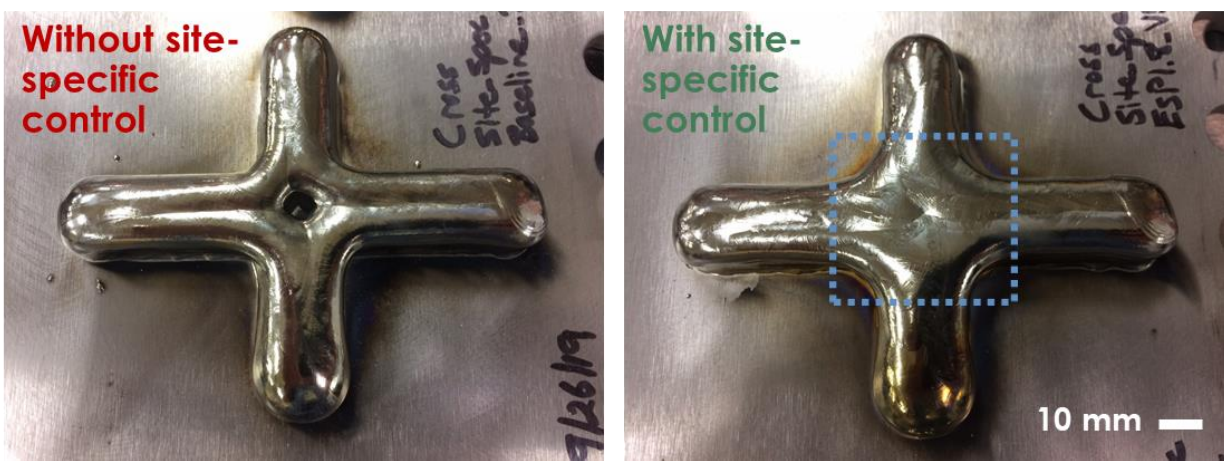

Figure 6: Case Study Cross Geometries for Demonstration of Volumetric Defect Mitigation; Baseline Case (left) and Site-Specific Case (right); Inside Bounding Box: Melt Pool Size Set-Point Increased 80%, Print Speed Decreased 37.5%, and Laser Power Modulated Automatically Under Closed-Loop Control; Material is Ti-6Al-4V