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Fabrication and evaluation of freeform surfaces in Directed Energy Deposition

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Abstract

Additive Manufacturing (AM) represents a paradigm shift in fabrication methodologies, enabling the creation of intricate geometries through sequential deposition. Among AM processes, Directed Energy Deposition (DED) is a metal-based technique that is particularly relevant for repair and remanufacturing applications, especially for high-value components. When coupled with 5-axis CNC, DED offers the unique ability to construct freeform surfaces, such as those typically found in the aerospace, marine and automotive industries. The focus of this research is to elucidate the interdependencies between the capabilities of a DED system and the achievable dimensional accuracy in freeform structures. To this end, on the basis of a parametrization approach, a comprehensive methodology has been formulated to tailor the design of a sinusoidal freeform to the capabilities and constraints of the specific DED system, taking into account, for example, the deposition head configuration and the number of controlled axes. The dimensional accuracy of the fabricated freeform was evaluated using 3D scanning technologies. The results showed that thermal distortion could significantly affect the geometry and may require thermal compensation. Additionally, acceleration transients may require appropriate path control strategies. The findings of this study offer valuable insights for future research on the influence of critical process parameters and production strategies on the dimensional accuracy of freeform components by DED.

3D printing, Accuracy, Manufacturing, Surface

1. Introduction

Additive manufacturing (AM) has developed significantly in the past decade and is increasingly being used in various industrial sectors due to its ability to fabricate complex geometries, reducing material waste and having a positive impact on the environment [1]. Directed Energy Deposition of metallic powders using a laser beam as energy source (DED-LB/Powder) is a promising metal-based AM technology. In this process, the laser beam is focused on a substrate, generating a local heating area and a melt pool, while powder material is conveyed to the deposition area in an inert gas stream through a nozzle. The component is produced by the mutual motion of the laser beam and the substrate along a deposition path generated by computer-aided manufacturing (CAM). DED-LB is suitable for producing large and complex metal structures with high deposition rates, and for repairing and remanufacturing high-value components, finding broad application in the automotive, biomedical, and aerospace industries [2].

DED solutions are usually 5-axis CNC systems or complex arrangements where the head is integrated into a robotic arm. The enhanced flexibility provided by multiple degrees of freedom allows for the adaptation of the slicing direction to the surface normals, overcoming the traditional 2.5-axis approach of powder bed systems. Multi-axis deposition represents a significant shift in the AM paradigm. Depositing material in different planes based on the variable slicing direction, and preventing collision between the deposition head and the deposited layers becomes significantly more complex. Therefore, advanced pre-process software support is required for manage the process effectively. Numerous articles in the literature have explored these aspects. As a starting point for multi-axis AM, Murtezaoglu *et al.* [3] emphasised the importance of decomposing the part geometry into discrete volumes, that will be deposited in sequence. Regarding the build order, Ramos *et al.* [4] proposed a strategy to determine the optimal slicing approach and building sequence for each decomposed volume. This involves solving a global optimisation sub-problem, which minimises the staircase effect and building time for each volume. The deposition of successive volumes may require several re-orientations of the substrate during the building process, and the previously deposited volumes could interfere with the deposition trajectories. Moreover, curved three-dimensional paths may result in build-up peaks where transition areas are present due to an increased curvature or reoriented axes. Another concern arises from the need to prevent the molten pool from spilling over the sides of the components [1]. To achieve this, the deposition head should be normal to the substrate or the previous deposited material. According to Xiao *et al.* [5], there is a shortage of automated process planning software that fully supports the use of 5-axis machine tools.

The flexibility of DED-LB systems enables the deposition of support-free freeform surfaces, even those with small thickness. Freeform surfaces, defined as surfaces containing one or more non-planar non-quadratic surfaces, are generally represented by parametric or tessellated models. Freeform surfaces have been widely used in various engineering applications, such as aerospace, automotive and mould industry [6]. Although DED has been shown to be effective in fabricating complex freeform geometries, current research primarily focuses on process planning and evaluating manufacturability of specific case studies, making generalization difficult [7, 8].

Exploring the boundaries of freeform manufacturing by DED, this investigation proposes a parametric design approach for freeform surfaces, wherein the surface parameters are adjustable based on the geometric characteristics inherent to the DED system. More specifically, a shaping algorithm is developed to design a sinusoidal freeform surface taking into account specific DED system constraints such as the deposition head configuration, the laser beam diameter, the number and type of controlled axes, to identify the limit conditions to avoid collision. Concurrently, the accuracy of the deposited geometry is assessed by comparison with the nominal geometry. The deposited geometry is evaluated by using a structured-light 3D-scanner. The observed deviations allow to evaluate the combined effect of geometry and deposition path management on the accuracy.

2. Methodology

This research presents a methodology for evaluating the capabilities of a generic DED system when fabricating a freeform surface. The freeform geometry is designed parametrically to conform to the geometric constraints of a generic DED system being investigated.

2.1 Freeform design

A surface generated by the 90° rotation around the *z'-axis* of the sinusoidal generatrix function was selected:

$$z'(x') = A \cdot \sin[B \cdot (x' + C)] + D$$

where *A* is the amplitude, *B* the frequency, *C* the phase shift, and *D* the vertical offset. A characteristic length (*L*) is used to define the cubic box containing the surface. This length is chosen based on the configuration of the DED system, such as the working volume, kinematics, or deposition head geometry, to prevent interference. The kinematic configuration of the system includes consideration of the number and type of controlled axes, joints, and capabilities of the computer numerically controlled (CNC) interpolator. These elements collectively determine the ability of the system to reach designated points in space (path) by following a specific temporal law (trajectory) [9]. The coefficients *A*, *B*, *C* and *D* of the sinusoidal function are computed numerically as the solution of a system of four non-linear equations. These equations constrain the starting point of the curve, S, at the coordinates $z'_S = 0$, $x'_S = L/4$, and the end point, E, at the coordinate $x'_E = L$. The tangency angles at these two points are equal to the minimum leading angle, *α*, and the maximum trailing angle, *β*, respectively, as depicted in Figure 2.

The three-dimensional surface has a biparametric (*u*-*v*) shape. The radii of curvature vary continuously along both the *u*- and *v*-directions. This approach ensures a smooth transition from the minimum leading angle, *α*, to the maximum trailing angle, *β*, accommodating the full motion capabilities of the DED system and ensuring the integrity of the deposition process. The freeform geometry can be classified as open inclined wall

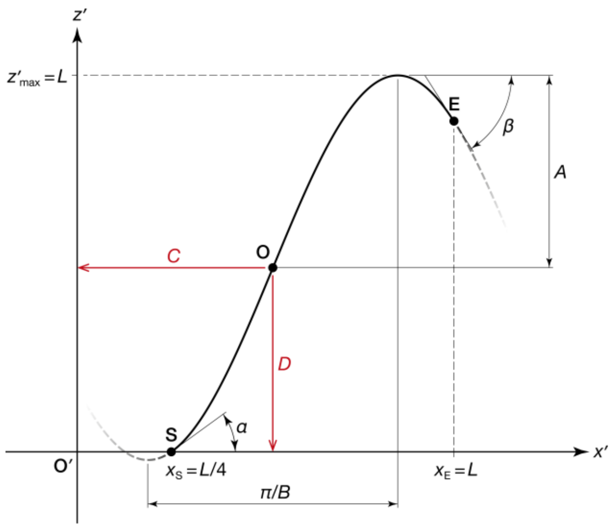

Figure 2. Parametric sinusoidal curve (O is the inflection point).

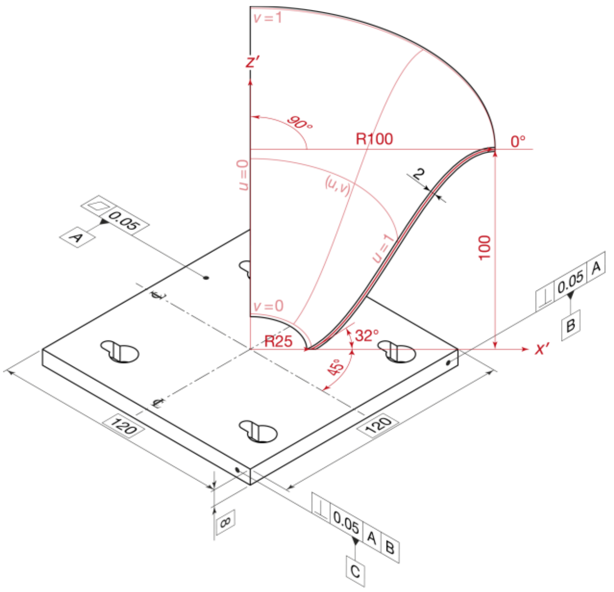

Figure 1. Freeform geometry and datum reference system.

according to the standard ASTM F3413-19e1 [10]. The three-dimensional model is realized in Rhinocheros by Robert McNeel & Associates (Seattle, USA) and is shown in Figure 1.

2.2 Programming

A variable direction slicing strategy is adopted, which means that the slicing follows the surface curvature in the *u*- and *v*-directions. Specifically, several parallel *u*-curves are defined by setting $v = v_0$, where v_0 values correspond to equally distant points on the *v*-direction based on the chosen value of slicing thickness. The slicing thickness is chosen based on the process parameters and the desired tolerance. The *u*-curves describe the path of the deposition head. At each point of the *u*-curves, the surface tangent in the *v*-direction determines the orientation of the deposition head.

A unidirectional deposition x'_E strategy is adopted to realize a single-track wall, with the mid-surface being the designed freeform surface. Furthermore, to ensure that the head axis is normal to the previous deposit, a key pathing constraint is implemented. This constraint orients the axis of the deposition head to the tangent to the freeform surface at all points.

The Grasshopper module in Rhinocheros is selected to slice the freeform surface. The deposition program is defined in the Mastercam software by CNC Software, LLC (Tolland, CT, USA). A linear interpolation is opted due to its more general applicability to any geometrical shape, adopting a tolerance of 0.02 mm. This value is lower than the typical accuracy of a DED system and is

Table 1. Constitutive parameters of the sinusoidal function used to model the generatrix curve of the freeform surface.

Sinusoid Parameter	Value
A	51.39 mm
B	3.75×10^{-2} rad·mm^{-1}
C	−58.09 mm
D	48.61 mm

Table 2. Process parameters used for freeform surface deposition.

Parameter	Value
Laser power, *P*	750 W
Travel speed, *v*	15.63 mm·s^{-1}
Layer height, *ΔZ*	0.5 mm
Powder mass flow rate, Q_p	9.2 g·min^{-1}
Carrier gas flow rate, V_{Ar}	5 L·min^{-1}

small enough to ensure a smooth surface, without implying the definition of an excessive number of points per each layer. In fact, an excessive number of points used to define the path of the deposition could result in difficulties from the control system to elaborate the motion of the axes with the right timing [11].

2.3 Fabrication

The freeform is tailored to the DED system under investigation and fabricated. In this study, the Laserdyne 430 by Prima Additive (Collegno, Italy) is used for production. It is a 5-axis DED system equipped with the TWA-160 roto-tilting table, by Tsudakoma (Kanazawa, Japan). The feedstock is a pre-alloyed stainless steel powder. To prevent the deposition head from colliding with the flat substrate, a minimum leading angle of 32° is required, which is achieved by tilting the table 58°. The kinematic configuration of the machine allows for a trailing angle of 0°, which is achieved by tilting the table 90°. A characteristic length *L* equal to 100 mm is selected for the fabrication. These assumptions lead to the coefficients in Table 1. Process parameters are set according to Pilagatti *et al.* [12] and are listed in Table 2.

2.4 Evaluation

The accuracy of the deposited geometry is evaluated by means of a structured-light 3D-scanner. 3D scanning is often employed in the assessment of freeform geometries, facilitating the acquisition of the actual deposited surface [13]. Specifically, the ATOS compact system by Carl-Zeiss GOM Metrology GmbH (Braunschweig, Germany) is used, with a resolution of 0.02 mm. Later, GOM Inspect 2021 is used to evaluate the deviations [14].

3. Results and Discussion

The deposition of the freeform was successfully completed (Figure 3). The surfaces were then 3D scanned by means of the ATOS compact system. The scanned geometry was then compared to the nominal one, which was constructed by offsetting the freeform surface by 1 mm on each side, taking into account that 2 mm is the track width at the given process parameters, as measured in preliminary experiments. Actual and nominal geometries were aligned by defining the datum reference system visible in Figure 1. The datum features were reconstructed from the scanned data using a best-fit algorithm. The analysis of the deviations led to the colour maps shown in Figure 4. Measured deviations were in the range ± 1 mm, with most of the occurrences being inside an even tighter interval, ± 0.6 mm. The resulting deviations were one order of magnitude larger than the chordal deviation of the deposition path generated by the linear interpolation. This proves that the segmentation did not significantly affect the final deposition accuracy of the freeform surface.

Figure 3. Deposited freeform geometry.

Overall, the deviations from the nominal geometry became more significant as the deposition progressed. The scanned geometry was found to be below the nominal one near the edges of the freeform surface from half height, while the opposite trend was observed at the centre of the freeform surface along its symmetry plane, where the scanned geometry was above the nominal one. The observed behaviour is consistent with the thermal evolution that occurs during the heating and cooling phases of the DED deposition. Especially, tangential compressive stresses arise from the thermal contraction of the material during the cooling phase. Along the *v*-direction, the deviations are localized in a middle area because the surface is constrained at the base to the substrate and is rigid at the top due to the increased curvature. Effects due to the acceleration/deceleration of the axes were observed near the edges. A peak was clearly visible at the left edge in Figure 4a, where deposition starts at each layer.

Profiles of the freeform geometry were extracted at three different values along the *u*-direction to provide information about the profile deviation from the nominal. The values were taken near the edge (u = 0.1), excluding the side effect caused by the transient, in the middle (u = 0.5), and in an intermediate zone (u = 0.3). Results are shown in Figure 5. Once again, it can be seen that the deviation from the nominal profile is very limited in the lower half of the profile and comparable for the three sections, whereas the largest deviations are observed in the upper region near the edge, with the actual upper surface being approximately 1 mm below the nominal one.

Finally, in assessing the quality of the achieved geometry, particular attention was paid to the leading and trailing edges of the surface. Leading and trailing angles were measured on the three sections. To avoid the effect of the first deposited tracks,

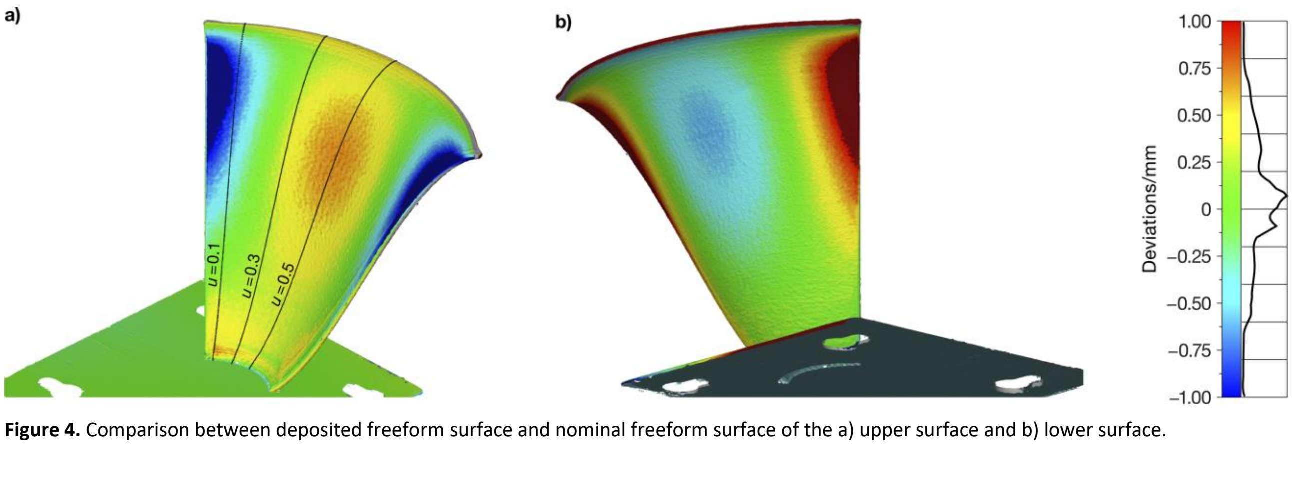

Figure 4. Comparison between deposited freeform surface and nominal freeform surface of the a) upper surface and b) lower surface.

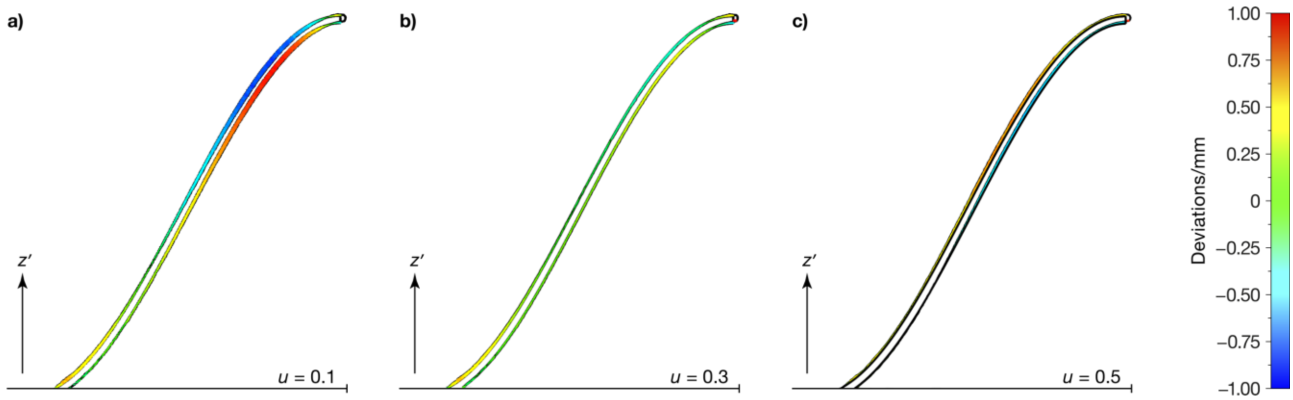

Figure 5. Section comparisons between deposited freeform surface and nominal geometry for a) u = 0.1, b) u = 0.3 and c) u = 0.5.

the leading angle was measured at a distance of 3 mm along the v-direction from the S point. At this measurement point, the tangency angle is 38.2°. The combined uncertainty assessment also incorporated the resolution error of the measuring instrument [15]. The mean value of the leading angle was determined to be (37.9 ± 1.8)°. In this context, a bilateral t-test with a 5% Type I error was conducted to compare this mean value with the nominal value. The p-value obtained for the leading angle was 90%, indicating that the null hypothesis cannot be rejected. Similarly, the trailing angle was measured at (86.1 ± 1.0)° with a p-value of 6%, also above the significance threshold. These values are promising, suggesting that the measurement accuracy is within acceptable limits.

4. Conclusions

This work proposes a novel method for assessing the capabilities of a generic DED system in the production of a freeform geometry, combined with the evaluation of the freeform accuracy. The manufacturability of the freeform geometry was ensured by the methodology adopted, which took into account the physical constraints of the system under study in the design phase. The 5-axis programming of the deposition path was developed by three-dimensional slicing, to follow the tangent to the generatrix curve, and linear interpolation technique. The geometric accuracy of the deposited freeform surface, captured by an optical scanner, was within the typical capabilities of the DED-LB system.

The availability of an evaluation method for the manufacturing potential of DED for freeform surfaces is particularly useful for industries where such geometry may be used for advanced applications. The proposed methodology allows for comparative analysis of DED systems. While the approach is promising, its current application is limited to controlled experimental conditions. Future research should be extended to real-world manufacturing environments to investigate the robustness of the process under varying conditions.

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