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Development of an additive and subtractive hybrid manufacturing process planning strategy of planar surface for productivity and geometric accuracy

Weijun Zhang¹ · Masakazu Soshi¹ · Kazuo Yamazaki¹

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Abstract

The directed energy deposition (DED) process enables the production of near net shape parts in the starting form of either powder or wire melted by a focused energy source, such as laser. The target geometry is then built layer by layer. In theory, engineering components with complex shapes can be fabricated with a single setup using a hybrid CNC machine tool, which has capabilities of both DED and traditional subtractive machining processes. However, the issue of inaccurate DED deposited geometry and insufficient material deposition results in the repetition of the hybrid process to achieve the goal geometric dimension. This paper presents a generalized strategy for different materials that plan DED toolpath for the planar geometric feature to achieve its required final geometric dimension by using only a single hybrid manufacturing cycle based on simulated results and validate the strategy experimentally by using a hybrid CNC machine.

Keywords Directed energy deposition (DED) · Planar · Geometry · Additive manufacturing

1 Introduction

Over the last 30 years, additive manufacturing (AM) technologies have undergone tremendous evolution [1–3]. AM technology, especially for metal applications such as selective laser melting (SLM) and directed energy deposition (DED) have gained much attention recently in academia as well as industry. The fundamental idea for metal AM technologies is to slice a solid model into many cross sections that are typically normal to the build direction. For each cross section, a high-power energy laser moves on the programmed path to melt the metal powder feedstock to fuse it to the part (or features onto parts). DED process parameters include powder flow rate, machine feed rate, and laser power. And, this technology can be used to directly manufacture complete and highly complex metallic parts with sophisticated geometries [4].

Although the DED process has an ability to produce more complex geometries compared with a subtractive method, the relatively poor surface quality and geometric tolerance of the deposited part requires post-processing by machining and/or grinding. To efficiently complete part fabrication and achieve accurate part geometries, multi-axis hybrid manufacturing, which integrates DED and conventional subtractive machining processes, has been introduced. A few hybrid machines are already available in the industrial market [5–7]. The capability to fabricate parts with a single setup decreases manufacturing time and potentially improves achievable part tolerances.

In theory, both the hybrid machine process and multiple machine process follow the workflow shown in Fig. 1a, but the hybrid machine allows the user to retain the same fixturing to reduce the additional source for errors if additional DED or subtractive machining processes are required. For successful hybrid manufacturing, the part dimensions after the initial DED step must be sufficiently overbuilt to allow for the finish machining of the surface. This can be accomplished by simply designing the DED toolpath to fabricate a part that is much larger than the final, finish machined target part, but due to the low material addition rate (MAR) and high cost of the feedstock of the DED process, any overbuilding must be kept to a minimum to control part costs.

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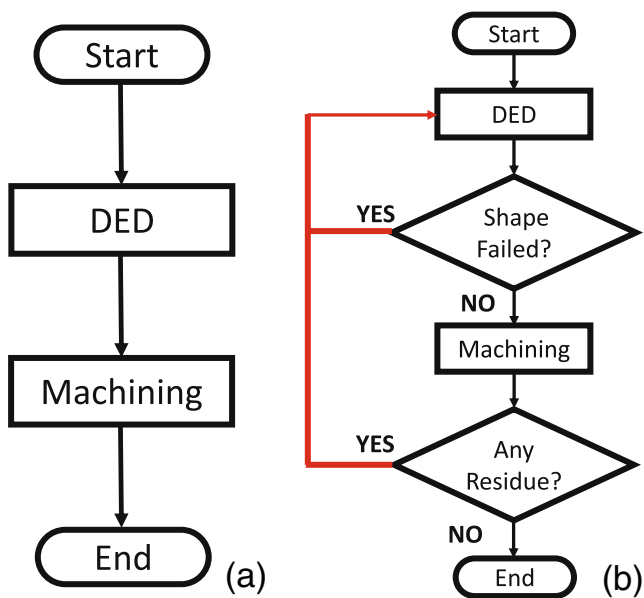


Fig. 1 Efficient hybrid manufacturing process (a) and inefficient, iterative hybrid manufacturing process because of DED underbuilding (b)

Gross underbuilds such as the top right corner of the thin wall shown in Fig. 2a as compared with the desired post-DED geometry in Fig. 2b are easily identified either qualitatively by the machine operator or qualitatively using a metrology device in the machine such as a touch probe. However, the slight underbuilding showed in Fig. 2c is more difficult to recognize prior to the completion of the subtractive process step. Insufficient deposition necessitates an additional DED process step to fix the underbuilt area, as shown in Fig. 1b. Once

enough material is deposited and the post-machining process removes material sufficiently, a surface like Fig. 2d should be observed. This repetitive process increases manufacturing time, thus minimizing the advantages of using a hybrid machine tool.

Substantial efforts have been made to improve the geometric accuracy of the part by investigating just the DED process and by using a hybrid process. Kono et al. studied the influence of the cladding path on the workpiece geometry [8]. Pinkerton et al. proposed a model for the geometry of laser-deposited tracks [9]. Shim et al. reported the method for the layer thickness setting to improve the geometric accuracy of the final part [10]. Suryakumar et al. modeled the bead's geometry to optimize the hybrid manufacturing process [11]. Kerschbaumer et al. investigated the toolpath generation for the hybrid manufacturing process between the additive and subtractive processes [12]. However, very few studies have been reported an investigation of the repetitive problem of the hybrid process when switching from the DED process to the machining process. Ideally, deposited parts made from a single DED process should be slightly larger than the target part to allow for a single subtractive finish machining operation. Therefore, the goal of this research is to improve the capabilities of the hybrid process by developing a strategy to deposit the optimal amount of material for post-processing DED parts.

This paper focuses particularly on the development of a hybrid manufacturing process planning strategy to fabricate a finish machined planar feature, as shown in yellow cuboid in Fig. 3a, that obviates the need for the time-consuming iterative process shown in Fig. 1b. The planar feature is a common DED application used for coating and repair with

Fig. 2 Failed thin wall (a), thin wall with good shape (b), thin wall with defects after machining (c), thin wall without defects after machining (d)

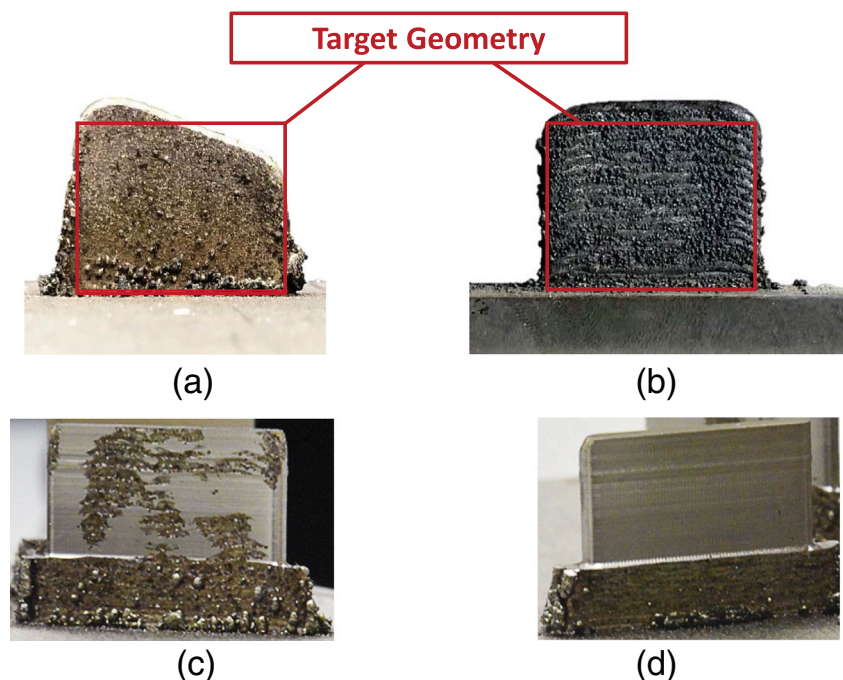
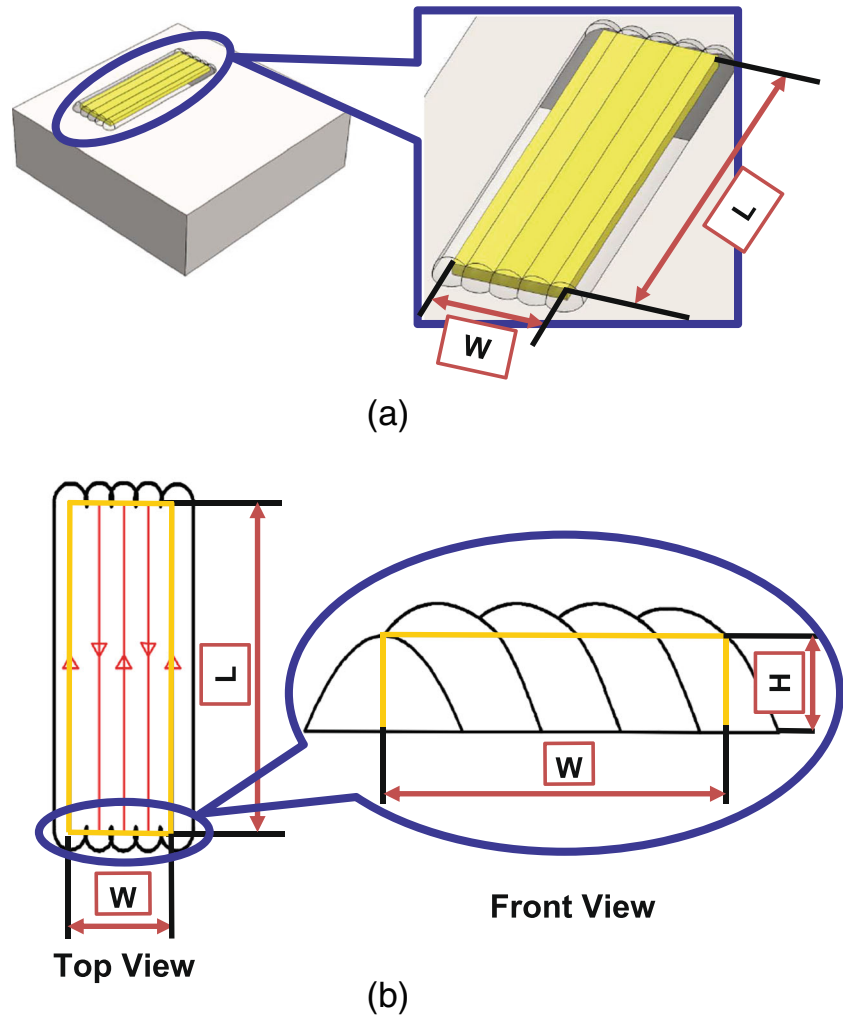


Fig. 3 A deposited (shown in transparent) and machined (shown in yellow) planar model (a), top and front view of the planar model (b)



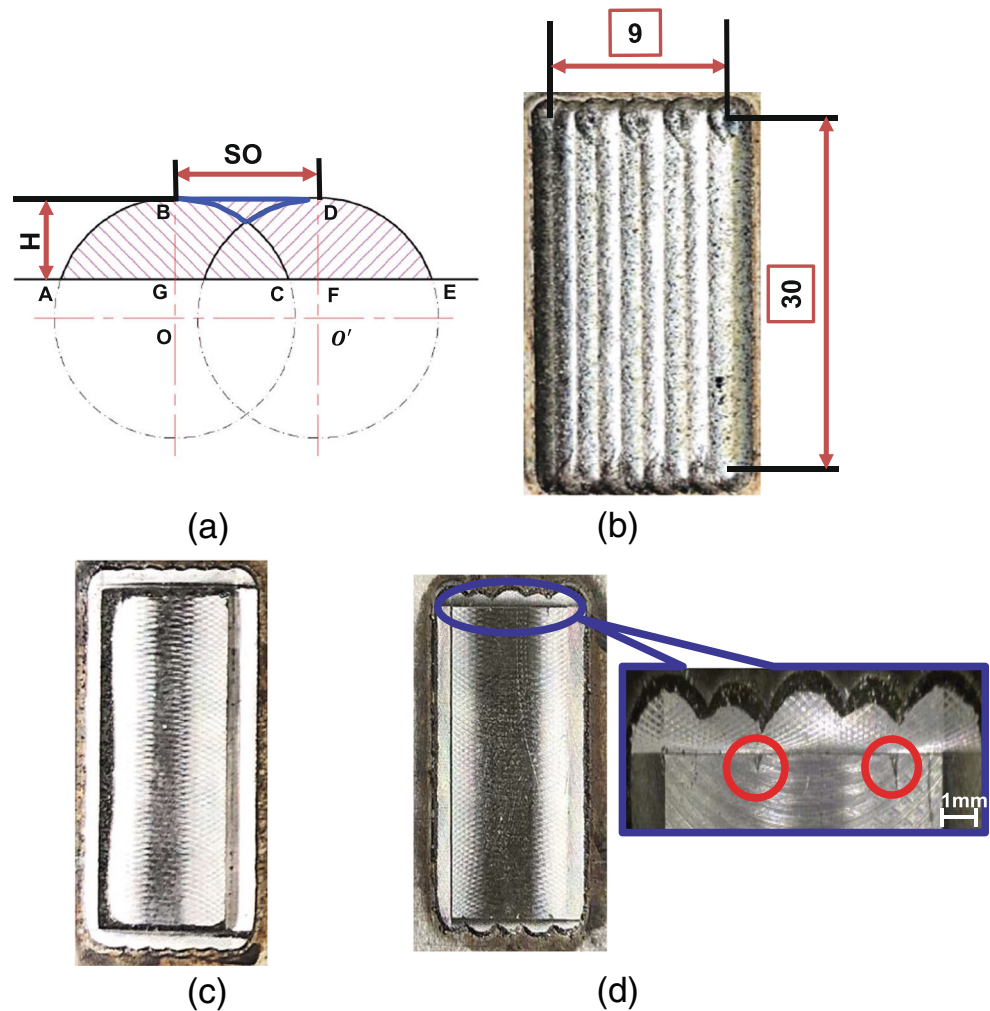
different materials [13–18]. If the DED toolpath for planar deposition is simply a zigzag toolpath where the laser spot center is used to trace the aerial extent of the desired final geometry, as shown in Fig. 3b, it is unlikely that sufficient material will have been deposited for the finish machining process since the individual DED clad profiles are hemispherical and the DED laser toolpath includes a stepover distance, Fig. 4a, that is less than the diameter of the clad width. The DED deposited part will have an uneven top surface and sloped edges, Fig. 4b. Errors in the final machined part are likely to include uncut material along the edges of the planar feature, Fig. 4c and d, and possibly uncut material at the top surface of the planar feature if the as-deposited DED height is not known in advance.

In this research, a generalized hybrid manufacturing process planning strategy for the fabrication of a single-layer planar feature is presented. The process planning methodology is easily implemented, applicable over a wide range of stepover distances and DED parameter values, and eliminates the need for iterative experimentation to develop an optimal

hybrid process plan to ensure sufficient material is deposited without resorting to expensive, inefficient gross overbuilding of the planar feature. Utilizing the results of an easily calibrated analytical model for DED planar feature height and an improved DED contour finishing toolpath, the method can quickly and robustly produce suitable DED process parameters for single-layer planar feature parts. The process planning methodology can be summarized as:

1. Calibration of a recursive analytical model for predicting a single-layer planar feature height using the work of Ocelik et al. [19] using the measured height and width from a single-line DED clad experiment
2. Computation of a logarithmic regression fit between stepover and final finished machine height from the model output
3. Selection of zigzag toolpath stepover distance from the logarithmic regression trend line
4. Addition of an improved DED contour finish passes to the zigzag toolpath.

Fig. 4 Stepover definition of a DED toolpath (a), top view of an as-deposited DED planar feature (b), uncut area edge after machining a planar feature (c), and detail of uncut area at the edge of a planar feature after machining (d)



The developed methodology was found to be robust to achieve the desired geometrical accuracy over a wide range of stepover distances and DED parameter ranges at one time.

2 Materials and methods

2.1 Hybrid manufacturing experiment setup

In this study, hybrid experiments for the planar feature were performed on the LASERTEC65 3D Hybrid. The experimental setup is shown in Fig. 5. This is a 5-axis machining center with additive and subtractive capabilities which are equipped with a Siemens 840d NC controller, 2500-W fiber-coupled diode laser with a 3-mm laser spot diameter, coaxial deposition nozzle, disc-type powder feeder system that delivers metal powder from powder hoppers via pressurized argon gas, and a spindle with the maximum rotational speed of 20,000 RPM.

Gas atomized stainless steel 316L-Si metal powder manufactured by MetcoClad with diameters between 45 and

125 μm was used as feedstock. The composition of 316L-SI is given in Table 1. Substrates with dimensions of dimensions 102 mm (W) by 102 mm (L) by 25 mm (H) were fabricated from AISI 316L stainless steel bar stock. A bandsaw was used to cut the substrate to approximate size and the faces were

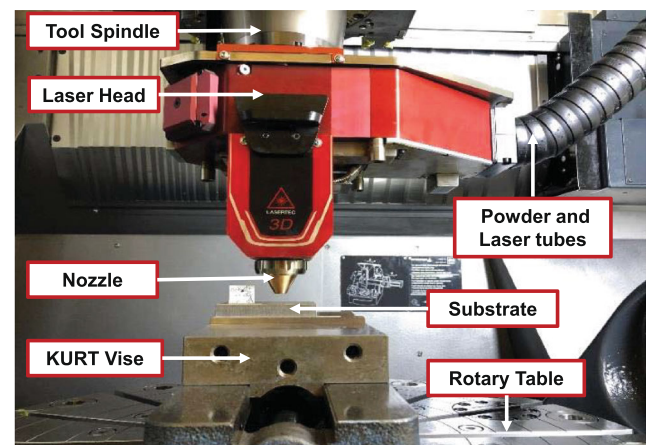


Fig. 5 Experiment setup in LASERTEC65 3D Hybrid

Table 1 Material compositions of stainless steel 316L powder (wt%)

Fe	Ni	Cr	Mo	Si	Mn	C	Others
Balance	12.0	17.0	2.5	2.3	1.0	0.03	≤ 0.5

milled to achieve a clean, flat surface. The substrate was fixed using a vise, as shown in Fig. 5, during both DED and machining.

Planar features were deposited using zigzag DED toolpaths where the center of the laser traversed the length of the desired planar length and overlapped the previous laser paths by a distance defined by the percentage of the laser spot size, referred to as the stepover. Enough paths are deposited to cover the aerial extend of the final desired width of the planar feature. During methodology development experiments, the target finish machined planar features had dimensions of 9 mm width and 30 mm length. Zigzag toolpath stepover distances ranging from 25 to 75% of the laser spot diameter (0.75 mm to 2.25 mm, respectively) were tested. The four sets of DED processing parameters shown in Table 2 were tested during methodology development, including typical DED parameters, aggressive DED parameters, higher powder flux parameter, and lower powder flux parameter. Aside from the planar feature experiments, single-line clads with typical, aggressive, higher powder flux, and lower powder flux parameters were performed as well and its geometrical feature is used as input parameters for an analytical model.

Higher feed rate DED parameters were derived by maintaining the values for energy flux (EF) (1) or powder flux (PF) (2), where P is the laser power, F is the laser feed rate, d is the laser spot diameter, and $\dot{m}$ is the powder mass flow rate.

$$EF = \frac{P}{F*d} = \frac{\text{energy}}{\text{area}} \quad (1)$$

$$PF = \frac{\dot{m}}{F*d} = \frac{\text{mass}}{\text{area}} \quad (2)$$

EF and PF were used to derive DED process parameters since PF has been reported to be predictive of DED clad height [20] and EF must be maintained to ensure deposited material quality is maintained [21]. When aggressive DED parameters

are used, PF or EF parameters are kept constant. By keeping PF and EF constant by proportionally increasing P , F and $\dot{m}$, the productivity of DED can be increased while part geometry is maintained.

Post-DED finish machining was done by milling with a 12-mm diameter MSE430 4-flute end mill from NS Tools using the cutting conditions in Table 3. Contour milling was done using a single, continuous up-milling pass. Face milling was done with a bidirectional toolpath and a stepover of 2 mm.

2.2 Part measurement and data analysis

The dimension of the deposited planar feature was measured using a $\mu\epsilon$ LSM2 diffused laser mounted in the Micro-Vu Excel HC502 metrology machine. Height data from the planar feature was collected with a 0.05-mm sampling pitch with relation to Cartesian coordinates. Prior to data analysis, raw height data was filtered using a fast Fourier transform (FFT) with a 0.8-mm wavelength filter per ISO No.13565-1 [22]. After filtering the height data, the inscribed rectangle within the measured clad that had the largest area was computed using an algorithm written in MATLAB.

2.3 Strategy development procedures

To resolve the geometric issues of the deposited planar, which was mentioned in Section 1, and develop a toolpath strategy, experiments are performed and analyzed in two stages as shown in Fig. 6.

To start, a planar surface deposition was attempted based on the target geometry with a conventional toolpath. The zigzag toolpath with length equal to the planar feature and a stepover equal to the laser spot radius (equivalent to 50% stepover) was used. An example of the deposited planar is shown in Fig. 4b. In the next step, the planar feature's height data points were acquired using a laser on the Micro-Vu metrology machine and filtered using an FFT. After, the zigzag cladding toolpath can be modified through data analysis to deposit enough material around edges of the surface for the post-milling of the desired planar feature width and length. This flow is shown on the right side of the flowchart in Fig. 6. The correct perimeter deposition was studied by slightly

Table 2 DED parameters used for deposition of 316L

	Feed rate (mm/min)	Powder flow rate (g/min)	Laser power (W)	Energy flux (kJ/cm ²)	Powder flux (g/(cm ²))
Typical DED	1000	13.5	1800	3.6	0.45
Aggressive DED	1800	24.3	2500	2.78	0.45
Higher powder flux	1800	30	2500	2.78	0.56
Lower powder flux	1800	13.5	2500	2.78	0.25

Table 3 Typical milling parameters for 316L

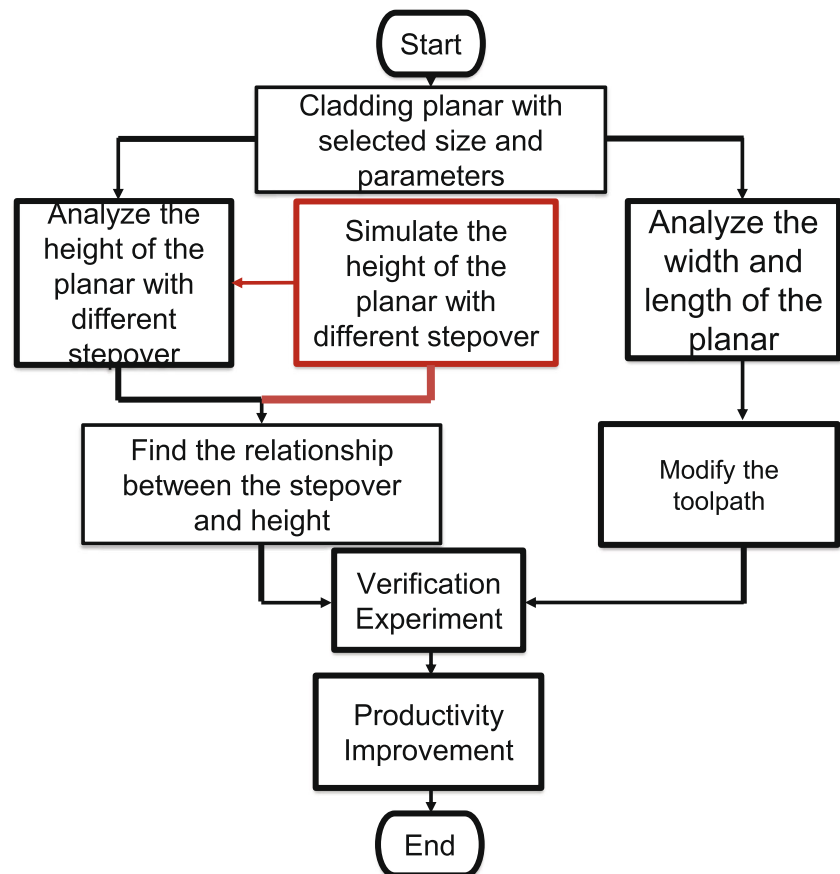
Tool diameter (mm)	Feed rate (mm/min)	Spindle speed (RPM)	Cutting speed (m/min)	Chip load ($\mu\text{m/tooth}$)	Maximum axial depth of cut (mm)	Face milling stepover (mm)
12	380	1600	60.32	59.4	1	2 mm

modifying the traditional toolpath, while the height of the planar has been optimized by simulation and experiments based on different stepover of the toolpath.

The planar feature was deposited using stepover ranging from 25 to 75% and the relationship was found between the machined goal height of the planar feature and different stepover from the planar height data analysis. Also, a recursive model with different assumed mathematical curves proposed by Ocelik et al. has been adopted by writing a script in MATLAB to predict the height of the planar with the different toolpath stepover [19]. The results from the recursive analytical model and experimental model can then be compared. This flow is shown on the left side of the flowchart in Fig. 6. Subsequently, based on the discovered relationship between the height after

cutting process and stepover from the experiment or analytical model, the user may determine the required stepover of the zigzag toolpath used in DED based on a goal machined height.

Using this technique, which is the modified toolpath and the determined stepover for zigzag toolpath, the planar feature should meet the goal dimensions within the first hybrid process and without any further corrections. Verification experiments were conducted with planar features of randomly selected target dimensions to verify the strategy performance. Once the method has been verified based on the experiment, the DED parameters can be optimized by increasing the feed rate while maintaining PF in order to build the same height and size of the planar but reduce the processing time. The relationship between goal

Fig. 6 Research progress flowchart

height and toolpath stepover values has also been observed for higher and lower PF values.

3 Results and discussion

3.1 Planar feature perimeter compensation method

As Fig. 7a shows, the rectangle with the red outline is the calculated largest cross section from the scanned data of planar feature surface deposited with 50% stepover (and therefore the largest width of the planar) achievable after the post-machining process. A comparison of the maximum finish machined width (red) with the target width of 9 mm (blue) indicates that an insufficient amount of material has been deposited for finish machining. In this case, both edges of the planar along its length direction need compensation to deposit enough material for the subsequent cutting process. The displacement difference between the blue rectangle and red rectangle is approximately 0.16 mm based on the point cloud data analysis. Since the clad radius is approximately 1.5 mm, which is significantly larger than 0.16 mm, adding one more clad path on both sides of the planar along its length direction is enough to compensate for the missing material on each side. For the length of the planar, as shown in Fig. 7b, the difference between the largest planar cross section achievable (red) and the desired planar cross section (blue) is around 0.735 mm, which is also still less than a single clad radius. Thus, the same compensation method along the width direction of the planar can be applied to ensure enough length of planar for finish machining. Similar results can be observed during planar deposition experiments over the range of stepover values.

Based on this analysis result, two different contouring compensation toolpaths have been adopted. The first toolpath is

the regular zigzag toolpath plus a contouring toolpath along the goal length and width of the planar, as shown in Fig. 8a. In Fig. 8, the red line represents the portion of the toolpath when the laser is on, while the blue line and green lines represent the portion of the toolpaths when the laser is off. Figure 9 shows the contouring machined result of applying the contouring technique shown in Fig. 8a. As can be seen in Fig. 9 a and b, there is still an insufficient amount of material deposited at the corners of the planar surface over the range of stepover values tested. More specifically, a notch exists after machining because there was no material there to machine. This is due to a large concentration of laser energy at the corner occurred, as the machine needed to quickly pause to change before moving in another direction. The instantaneous pause is inherent to the acceleration and deceleration of servomotors on different axes when changing toolpath directions in CNC machines. Due to the unsatisfactory results in the corner from the first technique, the toolpath technique shown in Fig. 8b was applied. This technique adds triangular non-cladding movements. Using this toolpath, the corners will have enough material because the deposition head makes two passes over the same corner of the planar after switching toolpath directions. This ensures enough deposition at the corners. With the second contouring toolpath technique, there is no defect left on the surface of the planar feature after the cutting process a large majority of the time. In order to make sure the contouring toolpath can build enough material at the corner every time, 1.5 mm (laser spot radius) of extra deposition on both front and back sides of the planar feature along the length direction applied, as shown in Fig. 8c. Using this conservative addition, enough material is always deposited with enough material for the cutting process. Figure 10 shows that the planar feature clad with 50% stepover zigzag toolpath and a second method for contouring compensation can achieve its goal perimeter dimension without any defects on the planar feature's side after the contouring machining process.

Fig. 7 Front view of data points of planar (a), side view of data points of planar (b)

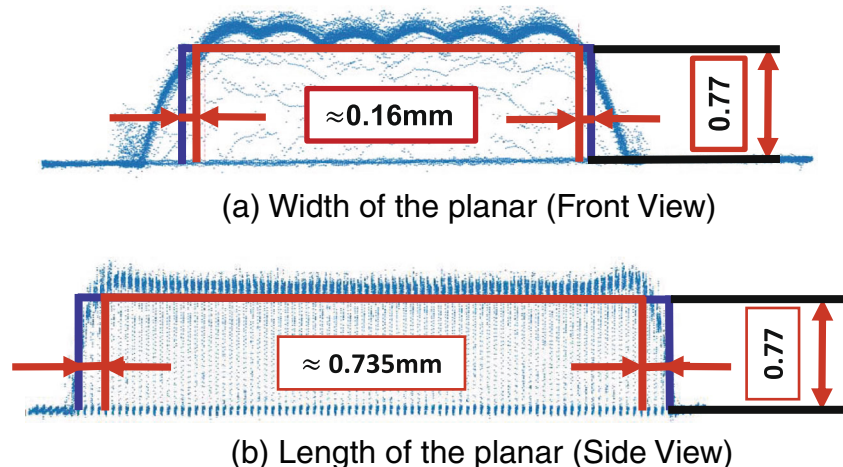
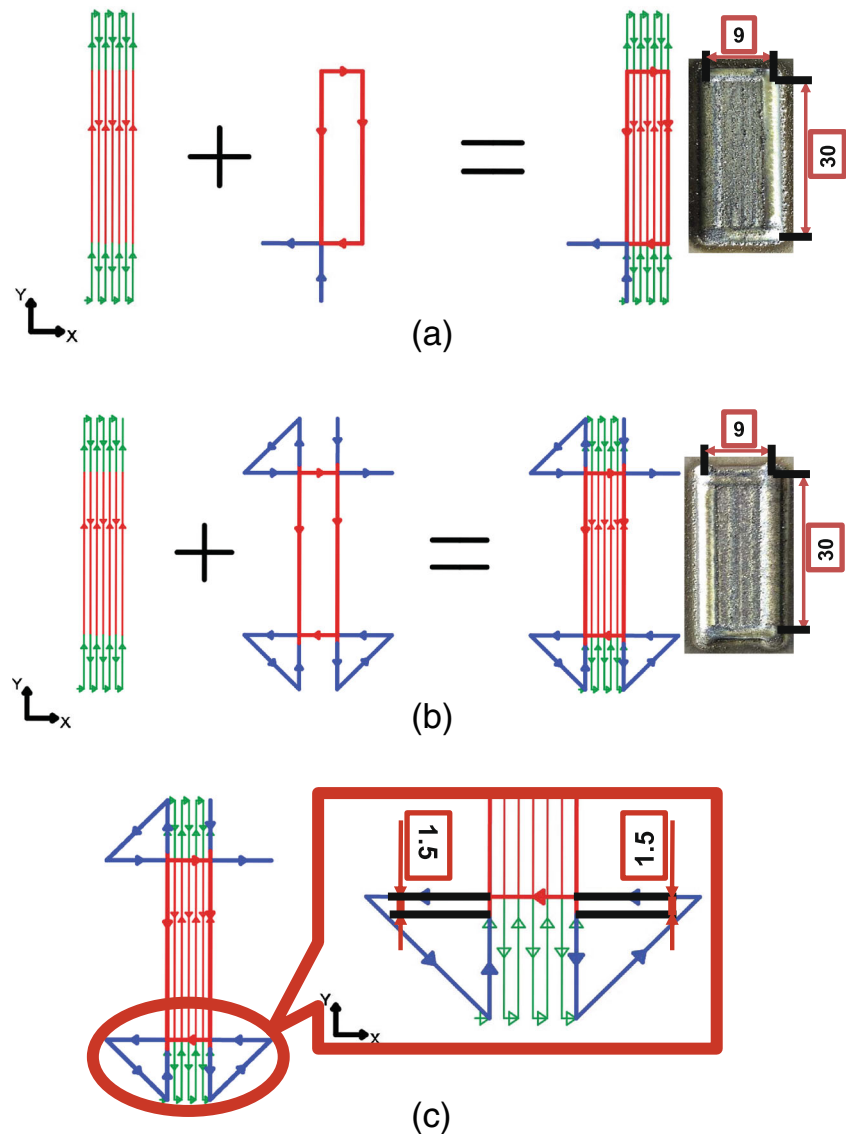


Fig. 8 Rectangular contouring compensational toolpath (a), contouring compensational toolpath with triangular non-cladding movements (b), and detail of corner overtravel on contouring compensational toolpath (c)



However, this only involves the goal width and length of the planar feature and not the goal clad height. The stepover of the toolpath determines the goal height and will be introduced in the next section.

3.2 Planar feature height prediction method

The height of the planar feature must be controlled as the required layer thickness varies for different applications. The height is mainly determined by stepover provided that the deposition parameters stay the same. The relationship between the deposition height and stepover can be obtained either by experiments or simulations. However, an experimental procedure requires a series of deposition experiments with different stepover settings, and thus, it is a time-consuming task. Therefore, a simulation-based prediction is preferred. Using

the model from Ocelik et al., the final machined planar height can be predicted and can then be used for verification after the manufacturing process.

To define this recursive model, there are three main parameters other than stepover: a user-chosen shape function to describe the cross-sectional profile of the single clad feature and the clad width and height from a physical single-line clad. Different shape functions include the arc, parabola, sinusoid, and ellipse, which are shown in (3), (4), (5), and (6), respectively. The output from this simulation is a cross-sectional area of the entire planar in which the largest machined rectangular cross section is inscribed. Assumptions of this model include:

1. The profile of the shape does not change for the following cladding if the DED process condition keeps constant.

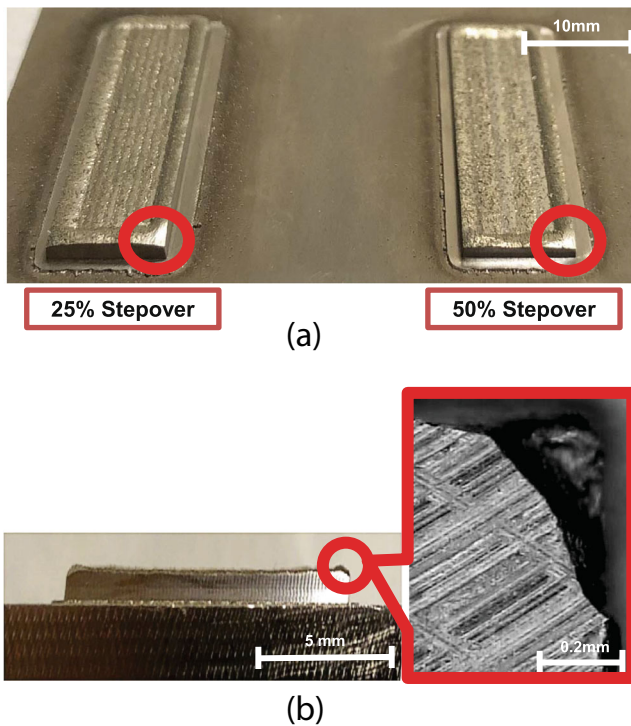


Fig. 9 Underbuilt corners of planar feature (a), and detail of underbuilt corner ($\times 315$ magnification) (b)

The width and height of the clad profile are assumed to be known.

2. The width of the clad is controlled by the EF during the DED process.
3. The amount of the clad material keeps constant during the following cladding tracks if the PF is constant during the DED process, which means the area of the cross section of each clad is assumed to be the same for the constant DED PF.
4. The shape profile functions can be assumed as 4 different commonly used functions. It can be parabolic function [23, 24] or elliptic function [25], arc function [26–28],

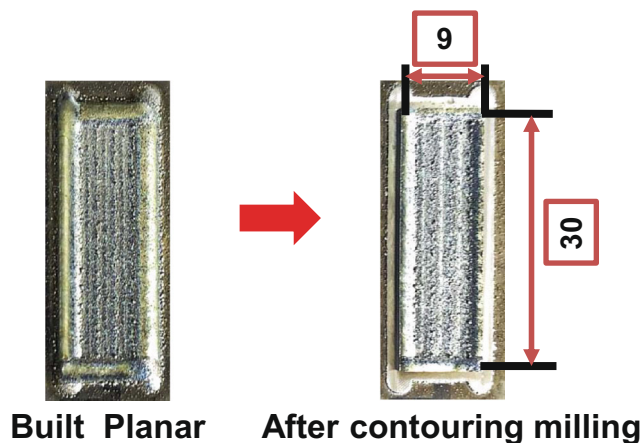


Fig. 10 Defect-free contour machined planar feature

and sinusoidal function [24]. The equations of the function are shown below:

$$\text{a. Arc : } f_i(x) = \sqrt{r_i^2 - (x - a_i)^2} + b_i \quad (3)$$

$$\text{b. Parabolic : } f_i(x) = a_i x^2 + b_i x + c_i \quad (4)$$

$$\text{c. Sinusoidal : } f_i(x) = a_i \sin\left(\pi \frac{x - b_i}{c_i}\right) \quad (5)$$

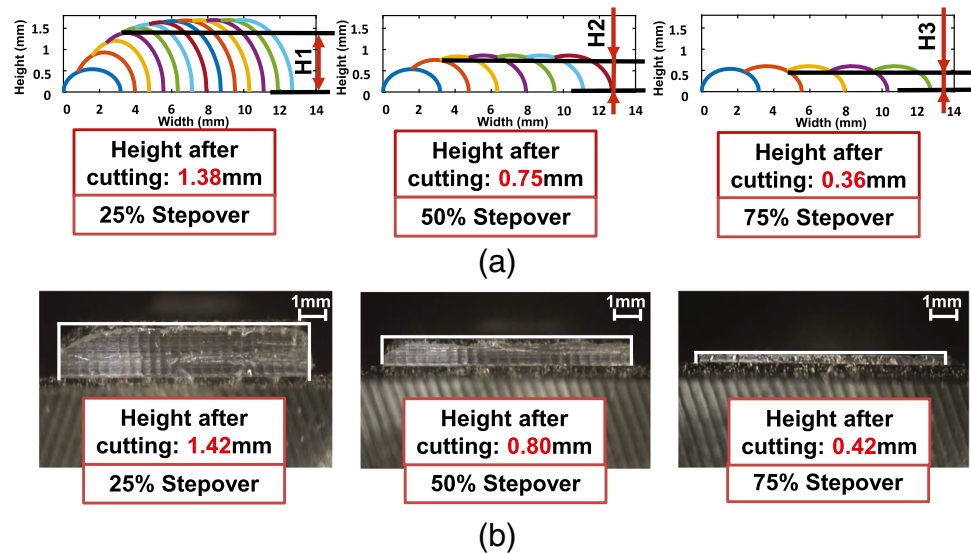
$$\text{d. Elliptic : } f_i(x) = b_i \sqrt{1 - \frac{(x - m_i)^2}{a_i^2}} \quad (6)$$

Thus, the most advantageous part of using this recursion model is that the material and deposition parameters need not be included. Instead, only the clad width and height from a single-line clad is needed to build the model. For this model, the Micro-Vu equipped with a laser measured a width and height of 3.1727 mm and 0.5376 mm respectively for a single cladding line, while applying typical deposition parameters as described in Table 2 with powder specified in Table 1. Using these results, multiple planar features' cross-sectional profiles were simulated for multiple stepover values (bounded by 0–100%). Figure 11 shows cross-sectional depositions using arc shape function. When applying this arc shape function, a logarithmic trend line was observed and showed generally that stepover is inversely related to final clad height, as shown in Fig. 12 by the red dotted line. Additionally, similar trends were found when applying the parabolic, sinusoidal, and elliptic shape functions, which can also be observed in Fig. 12. To find which shape function is most applicable, planar feature depositions were performed.

The post-machining height of planar feature with 25%, 50%, and 75% stepover is shown in Fig. 11b. These data points were also fit to a logarithmic line for the comparison of the simulated models, as shown by the dark red dashed line in Fig. 12. When comparing the post-machined height results from trends plotted in Fig. 12, it is clear that the elliptical function gives the best estimation from the experimental results. However, the aim of this goal is not to predict accurately, but rather try to eliminate insufficient deposition. Therefore, a conservative prediction is preferred. For this reason, the arc function was chosen for this study.

One of the biggest advantages of using this prediction method is that it can dramatically reduce a set of required experiments to obtain the relationship between height and stepover. If a different powder material is chosen for deposition, a single-line experiment is essentially needed to obtain the height and width of the model. Therefore, this proposed method can be used not only for this particular set of deposition parameters but also for different materials and depositions.

Fig. 11 Planar feature height prediction from a model by Ocelik et al. [19] with different stepover amounts (a), finish machined planar feature experimental result (b)



3.3 Effect of different DED parameters on the relationship

After generating the relationship between a planar feature's post-machined height vs. stepover using the simulation method from Ocelik et al. along with arc shape function and verifying the results experimentally, different DED parameters can be tested as well—most notably, aggressive DED parameters as shown in Table 2. In the aggressive DED parameters, feed rate, powder flow rate, and laser power were proportionally increased to increase productivity while maintaining constant PF or EF. Theoretically,

keeping PF and EF constant would yield a final clad geometry that is the same as if produced by typical DED parameters. The experimental results show that the aggressive DED parameters (solid blue line) yield an almost identical final height as compared with the typical DED strategy (dashed red line) in Fig. 13. The error bar in Fig. 13 represents the calculated standard deviation of height after cutting from three replicated experiments under each aggressive DED parameter. And, the analytical model shows similar results. It clearly shows that the aggressive DED parameters (dotted blue line) match the logarithmic trend of the final height as compared with the typical DED

Fig. 12 Finished machined height of planar surface feature from experiment and model by Ocelik et al. [19]

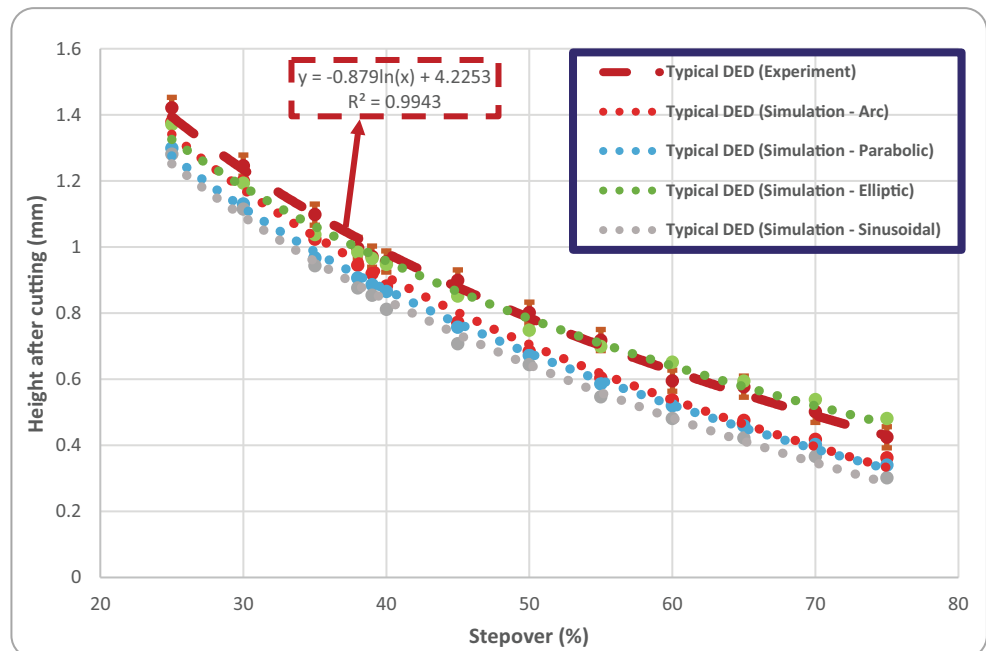
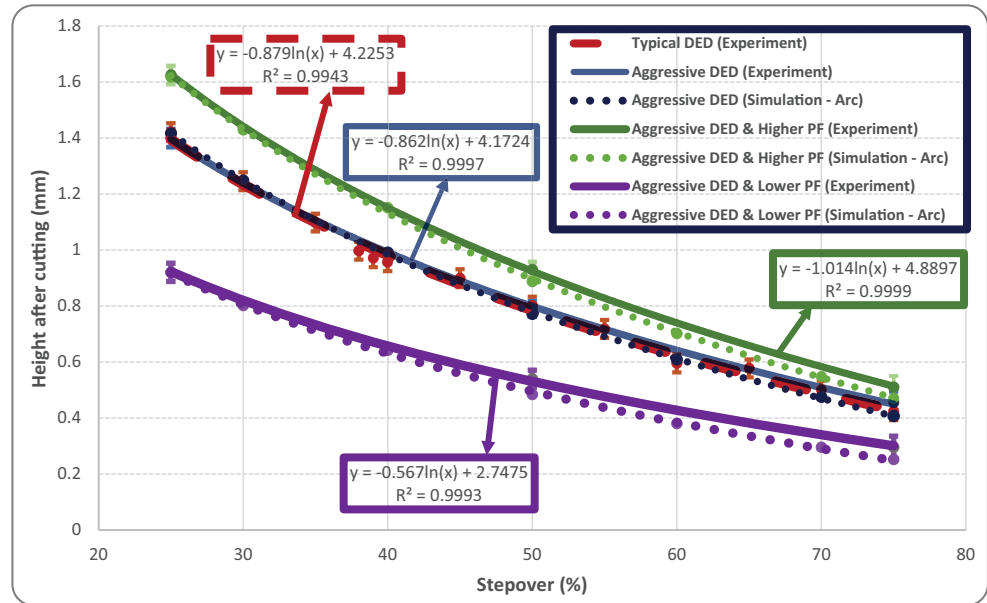


Fig. 13 Relationship between the height after cutting process and the stepover with different DED strategies



strategy (dashed red line). Therefore, using the aggressive DED parameters, the planar feature can be deposited in less time while achieving the same goal geometry of the height.

Based on the aggressive DED study result for planar, higher and lower PF parameters (shown in Table 2) were also tested against stepover. Results in Fig. 13 show the simulated trend line (green and purple dotted lines for higher PF and lower PF, respectively) yielded extremely similar data to the experimental results (green and purple solid lines for higher PF and lower PF, respectively). Thus, it is verified that the goal height of the planar can be achieved by changing either the powder flow rate or stepover. By only increasing the powder flow rate, the PF increases, which increases the clad height (explained in Section 2.1). The stepover can then be increased to produce the same goal planar feature height compared with the lower powder flow rate with lower stepover value. However, with a larger stepover, the planar feature can be deposited faster because the toolpath is shorter overall as compared with a planar feature with a small stepover.

3.4 Planar strategy and validation

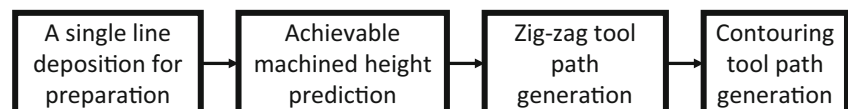
The developed planar deposition strategy for an additive and subtractive hybrid machine is summarized in Fig. 14.

First, a single-line deposition test must be performed to obtain a deposition height and width information for

given powder and deposition parameters. The obtained data is then used for the recursive model to generate the relationship between the achievable machined height and stepover. The relationship can be obtained also by experiments, but a simulation approach is preferred to reduce the preparation time. From this obtained graph, the optimal stepover is selected to avoid both insufficient and unnecessarily overbuild depositions. The next step is to generate a conventional zigzag toolpath with the selected optimal stepover. The last step is to apply the modified contouring toolpath with triangular non-cladding to the zigzag toolpath with decided stepover to deposit a planar feature with optimal sufficient material. This additional path ensures enough deposition at edges and corners. With this developed approach, one can assure that the deposition is sufficient to proceed for the machining process to finish the desired planar surface geometry.

To validate the strategy with a typical DED strategy, several planers with various dimensions were fabricated by using hybrid manufacturing processes. One of the dimensions has been conducted is 30 mm × 15 mm × 1 mm corresponding to length, width, and height, respectively, with aggressive DED parameters. The first step is to find the dotted blue curve line as shown in Fig. 13 by conducting a simple cladding line and by using Ocelik et al.'s analytical model. Second, a 41% stepover was selected by referring to the dotted blue line to yield a finished

Fig. 14 Developed strategy flowchart



height of 1 mm. Thus, the overall width can be divided by the laser spot diameter and divided by the stepover percentage of the laser spot diameter to reveal that 14 zigzag tool passes are required to achieve the goal. The equations are shown as follows:

If $\frac{W}{d \cdot \text{stepover}(\%)}$ can be divided exactly to be an integer

$$\text{Zigzag passes} = \left\lfloor \frac{W}{d \cdot \text{stepover}(\%)} \right\rfloor + 1 \quad (7)$$

If $\frac{W}{d \cdot \text{stepover}(\%)}$ cannot be divided exactly to be an integer

$$\text{Zigzag passes} = \left\lfloor \frac{W}{d \cdot \text{stepover}(\%)} \right\rfloor + 2. \quad (8)$$

where W is the width of the final planar feature, d is the laser spot diameter, and $\lfloor \cdot \rfloor$ indicates truncated division where only the integer portion of the operation is used.

Third, the proposed method of contouring compensation using triangular non-cladding toolpaths was applied to the edges of the planar feature. Finally, the contouring and milling process was conducted to reach its goal dimension. The planar built feature by just the DED process, after the contouring milling process and after the surface milling process are separately shown in Fig. 15 a, b, and c. The planar goal geometric dimension was achieved without any surface defect after conducting of the hybrid manufacturing process only once, which verifies the proposed strategy.

4 Conclusions and future work

The generalized strategy for manufacturing the accurate geometry for a planar surface feature in one attempt via an

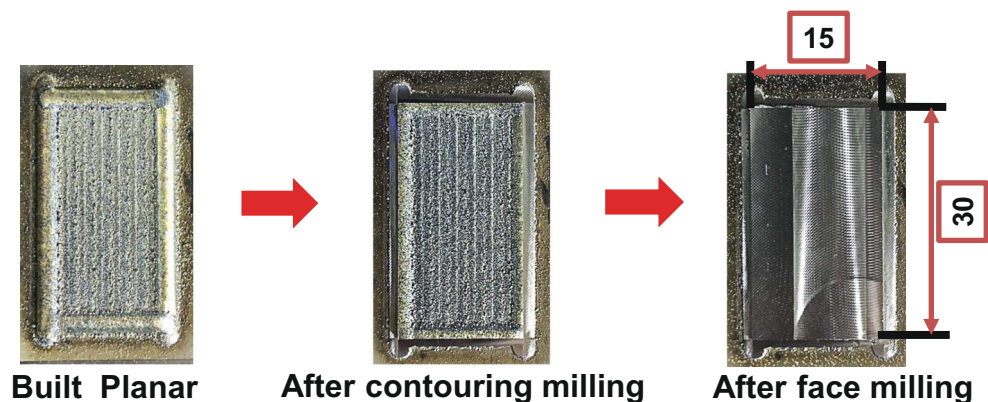
additive and subtractive hybrid machine tool has been studied and established in this paper. The different size requirements of the planar surface can be achieved. Materials must be slightly overbuilt in the additive process for the subsequent milling process but should be done optimally to avoid excess material usage and operation time. The planar surface with its goal dimensions has been successfully fabricated and verified via the experiment. The following conclusions have been found:

1. The contouring pass trajectory should be applied to deposit sufficient material for fully machining the edge and the corner of the planar surface. The contouring was valid regardless of the target planar sizes tested.
2. A relationship between stepover and final machined height has been found based on the simulation data and experiment data. It can be used to determine the stepover within the DED process if a certain goal height for the planar has been determined. A similar relationship with other materials can be achieved by a minimum number of experiments and simulations.
3. An aggressive DED strategy by increasing the feed rate, laser power, and powder flow rate can be applied to decrease the deposition time and lower the cost of the hybrid manufacturing process and thus improve the capabilities of the hybrid process.
4. The same planar surface feature height can be achieved through changing PF with different stepover by referring to the different fitting curve line with different PF. Higher PF can decrease the deposition time as well.

This generalized strategy can be applied with applications like the coating process to achieve accurate geometry of the planar surface with required width, length, and thickness only using the hybrid manufacturing process once.

Future work on this topic can be extended to the material mechanical properties study of the planar part fabricated via a hybrid machine. Mechanical properties, including microhardness, residual stress, and tensile strength, need to be

Fig. 15 Defect-free contour and face machined planar feature



investigated to further understand the application of the developed strategy.

Also, since the planar feature is a 2D geometric feature, energy accumulation does not significantly influence the geometry of DED built planar because the heat diffused into the substrate quickly. But for 3D geometric features such as the thin wall and cube, the same strategy cannot be applied due to energy accumulation during the layer by a layer deposition process. Thus, strategies for 3D geometries are also eager to be found to ensure the geometric features can be achieved within one hybrid manufacturing process. This way, the goal dimension of a composite industrial part composed of several basic geometric features can be fabricated faster and with lower cost by using a hybrid machine and by adapting different geometrical feature strategies.

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