A Novel Methodology to Manufacture Complex Metallic Sudden Overhangs in Weld-Deposition Based Additive Manufacturing

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Abstract

Amongst various additive manufacturing (AM) techniques for realizing the complex metallic objects, weld deposition (arc) based directed energy AM technique is attaining the more focus over commercially available powder bed fusion techniques. This is due to the capability of high deposition rates, high power and material utilization, simpler setup and less initial investment of arc based AM. Nevertheless, realization of sudden overhanging features through arc based weld deposition techniques is still a challenging task due to the necessity of support structures. The present work describes a novel methodology for producing complex metallic objects with sudden overhangs without using supports. This is possible by re-orienting the workpiece and/or deposition head at every instance using higher order kinematics (5-axis setup) to make sure the overhanging feature is in-line to the deposition direction. The proposed technique identifies the sudden overhangs form a CAD model (.stl) and generates an orthogonal tool path for deposition of the same. To validate this technique, objects with sudden overhangs (illustrative case studies) have been taken up for deposition. An In-house MATLAB routine has developed and presented for performing the same. Although this technique is suitable for any deposition process, it has been demonstrated using gas metal arc welding (GMAW) based weld-deposition, where the raw material to be deposited is in the form of a welding wire.

1. Introduction

Additive manufacturing (AM) is a process of joining the materials to build the objects from a 3-Dimentional computer aided design (CAD) data in layer by layer manner. AM also refers to a series of technologies that realize the components from CAD files by selectively depositing each layer at a time in very short span. Typically, AM process is contrasting traditional subtractive manufacturing methodology; where the unwanted material is removed in the form of chips from the block of raw material. In AM, the components “grow” from bottom to top till completion, after slicing the 3D CAD model into 2D layers (slices). Though its initial applications were limited to polymers, with the growth of technology; AM is now used for metallic components [1]. AM of metals had a significance impact on the components which are difficult to machine, time consuming and non-economical (i.e. titanium alloys and nickel based super alloys) to manufacture using traditional manufacturing processes.

Amongst the various AM processes available, fabrication of metallic components is feasible in Powder Bed Fusion (PBF), Material extrusion (Multiphase Jet Solidification), Sheet lamination such as Ultrasonic Consolidation (UC) and Directed Energy Deposition (DED) techniques. Figure 1 illustrates the broad classification and sub classifications of metallic AM processes available. Nevertheless, PBF and DED techniques are quite popular for realizing the complex metallic objects through AM technology. Commercially available PBF techniques (wherein a metal powder layered on a bed with equal layer thickness and the same is scanned by an energy source) such as Selective Laser Sintering (SLS), Selective Mask Sintering (SMS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) etc. use previous layer (fused and un-fused powder) to deposit the current layer overhang feature. Once the part is built, the coagulate powder will be dust off with the pressurised air. The similar arrangement is not yet available to the other AM techniques. However, the major drawback with the metal AM is the temperature distribution. The moving energy source or heat source used in all the above-mention processes induce heat either for melting (pre laid powder in case of PBF) the or for the melting and deposition (feed wire or powder in the case of DED) of the raw material. Which result in un avoidable temperature distribution over the substrate and the deposited component and affects the thermal residual stresses, part warpage, and inhomogeneous mechanical properties. Few authors have proposed the optimal path for deposition and dwell between the layers to minimize the thermal residual stresses, part distortion and change in the mechanical properties [2], [3]. M P Sefidi et al., has proposed a rule based path identification and deposition to minimize the inhomogeneous temperature distribution [4]. Erik et al., proposed inter layer dwell time between the layers to lower residual stress and distortion levels of the deposited component [5].

Very few attempts have been reported to manufacture of metallic objects through material extrusion (multiphase jet solidification) and sheet lamination (ultrasonic consolidation) techniques. In case of Multiphase Jet Solidification (MJS) process, a metal powder-binder mixture squeezed through a computer aided nozzle to realize a layer. Once the object is completed in layer by layer manner, the binder will be removed and the object will be directed to the sintering station for achieving the strength. On the other hand, Ultrasonic Consolidation (UC) is a hybrid sheet (metal) lamination AM technique. In which high frequency ultrasonic vibrations are responsible solid state bonding between two metallic foils and then a CNC contour milling operation is performed for achieving the dimensional accuracy and surface finish [6], [7]. But, aforesaid processes (both UC and MJS) are constrained to build simple straight walled components due to the process and machine limitations.

Figure 1: Broad classification of metallic AM techniques available.

Similar to PBF technique classification in Figure 1, based on the type of energy source used, the DED technique is classified as Laser based, Arc based and Electron beam based AM processes. Few DED processes such as Laser Engineered Net Shaping (LENS) and Electron Beam Free Form Fabrication (EBFFF or EBF^3) were also explored by several researchers for generating the complex metallic components [8]. Nevertheless, these processes are expensive. On this front, arc based weld-deposition techniques stand best for the manufacture of fully dense functional metallic components. This is due to its process capabilities like high deposition rate, high material and power utilization, simple & cost-effective setup, and without any need of a specially controlled environment [9]. Another important advantage of wire and arc-based AM technique is the manufacture of large scale or large structure components [10]. Few researchers have already realized the large scale or large structure components for aerospace and automobile applications. Which quite challenging in other metallic additive manufacturing techniques such as powder bed fusion techniques owing to its build volume limitations [11], [12]. Amongst the various arc-based welding processes (illustrated in Figure 1 and the highlighted technique used in the present work) available, the following have been successfully adopted for metallic AM applications:

- Gas Metal Arc Welding (GMAW): 3D Welding, 3D Welding and Milling (3DWM), Hybrid Layer Manufacturing (HLM), Wire and Arc Additive Manufacturing (WAAM) and Wire Arc Spray (WAS).
- Gas Tungsten Arc Welding (GTAW): Shaped Metal Deposition (SMD) and 3D Micro Welding (3DμW).
- Plasma Arc Welding (PAW): Hybrid Plasma Deposition and Milling (HPDM) and Micro Plasma Arc Welding (μ-PAW) etc.

Nevertheless, none of the above-mentioned arc based AM techniques is commercially available. These are developed merely for realizing a near net shape from a CAD model. Later on, machining operations will be performed to achieve industrial level surface finish and dimensional accuracy. As the benefits of GMAW based weld-deposition technique is impressive and dominating the other arc based techniques, the same is chosen in the present work. Although the methodology for realizing the components was the same, the suitable kinematic setup for each individual AM technique may be a little different. Based on the complexity of the geometry to be realized, especially in an arc (GMAW) based AM; components can be classified into three varieties viz., (1) objects with no overhangs (Zero overhang or vertical features or straight wall features), (2) objects with small overhangs and (3) objects with large overhang features. The objects with zero and small overhang features can be easily fabricated using 2.5-axis deposition by little over extension from the previous layer. But the objects with large overhangs demand higher order kinematics (5-axis) for continuous re-orientation. The large overhanging components are again sub classified into two groups such as components with gradually varying large overhangs and components with sudden or abrupt overhanging (nearly horizontal) features. Figure 2 depicts the various kinematic setups required for arc (GMAW) based AM based on the complexity of the geometry.

Figure 2: Various kinematic setups required for arc based AM.

In arc based AM, most of the works were narrowed and related either fabrication of fully dense or thin-walled straight features i.e. components with small or no overhangs [9], [13]–[24]. However, in the absence of universally applicable support mechanism; deposition of overhanging features remains one of the main challenges in AM. A separate support structure is often necessary for depositing the overhanging features. In case of PBF techniques like SLM, easily detachable supports made up of the same material is used to assist the manufacture of overhangs [25]. A similar procedure for DED based AM processes is not yet available. Small overhang features are usually possible with almost all the AM processes and also tolerate a little over extension from the previous layer. Nevertheless, deposition of large gradually varying overhangs and sudden overhangs with complex features without support structures is a challenging task in any AM process. This demands higher order kinematics which calls for inclined and/or orthogonal slicing and area-filling.

In general, elimination of support mechanism in deposition reduces the deposition time and post processing steps to fabricate an object. Adaptive slicing or adaptive special decomposition technique is one of the techniques to achieve the same and addressed by several researchers. Ren et al., proposed a decomposition approach for depositing the curved overhanging features without the use of support structures using adaptive slicing. In this approach, mainly the object is divided into non-uniform layers (i.e. different layer thicknesses) and then each layer is obtained through parallel slicing [26]. Apart from the adaptive slicing technique, double-sided layered manufacturing and multi directional deposition methods were tried by few researchers to minimize the quantity of support structures.

To eliminate the support structures for overhanging features, Sara et al., has used a double-sided deposition technique. In which the overhanging and non-overhanging region of the component were divided using a parting line. At first, the lower region was deposited in upside down direction and then flipping operation will be performed. Upon the flipped region the remaining object is the deposited and the same has been demonstrated using the FDM process [27]. Dwivedi et al., has used a laser based direct metal deposition (LBDMD) technique with multi directional deposition to manufacture large gradual overhang components like helix without the use of a support mechanism [28]. This was achieved by continuously varying the build direction in the normal direction of the helix. However, aforesaid methods are not fully automated. On the other hand, different research groups have adopted various higher order kinematic arrangements such as 8-axis robot, 6-axis robot and 5-axis CNC vertical milling centres for deposition of large overhang features without the use of support mechanism. The increase in degrees of freedom between the workpiece and the deposition head led to flexibility to manufacture more complex shapes with less time. But these methods demand optimal part orientation and suitable process planning techniques.

Ding et al., has used 8-axis robot (6-axis robot with additional tilting and rotatory axes) to manufacture complex overhanging features using LBDMD technique [29]. However, this technique is limited to complex revolved components. Kazana et al., suggested the positional weld-deposition technique for realizing various geometrical features such as horizontal, inclined and curved enclosed features with large overhangs [21]. These were demonstrated using 6-axis robot with WAAM process. Few research groups adopted hybrid manufacturing techniques (additive and subtractive operations on a single station) to fabricate complex overhang features through AM. Liou et al., integrated direct laser deposition process with the milling operation to build an overhang feature [30]. Based on the geometrical complexity of the feature, Suryakumar et al., proposed various build strategies with suitable kinematic setup required and the same was executed using HLM process [17]. Chen et al., used a 5-axis CNC accumulation process for depositing 3D surfaces without the usage of support structures by depositing the non-planar surfaces [31].

Panchagnula et al., proposed a higher order kinematic setup to manufacture large gradually varying overhang features without a support mechanism. In contrast to the uniform layer thickness with in a slice, an inclined slicing and layer deposition technique was used in this method [32]. This was achieved by suitably varying the processes parameters with in the layer. This process starts with the deposition of an inclined layer on a flat substrate. Based on the inclination achieved in the deposited layer, substrate was continuously re-oriented for the weld deposition. An intermediate face milling operation was also performed in between successive layers for z-scallop height. This process will continue till the entire object is made. A 5-axis CNC vertical milling centre with a GMAW based weld-deposition setup has been used to validate the same. In addition to the above, various thin-walled components with large overhangs without supports were also explored by the same group [9]. However, the same technique is not suitable for the components with large sudden or abrupt overhanging features such as nearly horizontal features. Which demands the re-positioning the workpiece at every instance to make sure the overhanging feature is in-line to the deposition direction. In addition to that a region based orthogonal slicing and area-filling technique is also essential for realizing the components with the sudden overhanging features.

To the best of authors knowledge and from the available literature, there were no significant efforts have been reported to manufacture complex and sudden overhanging features (features that are perpendicular to the deposition direction or nearly horizontal features) without support mechanism in related with arc based AM. The present work describes a novel methodology for producing complex metallic objects with sudden overhangs without using supports. This is possible by re-orienting the workpiece and/or deposition head at every instance using higher order kinematics (5-axis setup) to make sure the overhanging feature is in-line to the deposition direction. The proposed technique identifies the sudden overhangs form a CAD model (.stl) and generates an orthogonal tool path for deposition of the same. To validate this technique, objects with sudden overhangs (illustrative case studies) have been taken up for deposition. An In-house MATLAB routine has developed and presented for performing the same. Although this technique is suitable for any deposition process, it has been demonstrated using arc (GMAW) based weld-deposition, where the raw material to be deposited is in the form of a welding wire. The successive sections elaborate the experimental setup, methodology used for depositing the sudden overhang features along with three illustrative case studies in detail.

2. Experimental Setup

Realizing a sudden overhanging feature in an arc based (GMAW) weld-deposition process is still a challenging task and requires higher order kinematics integrated to a deposition system and/or to the workpiece. The present experimental setup used to realize the sudden overhanging features without supports consists of the following two sub-systems:

1. A positional interpolator (5-axis CNC vertical milling centre) and
2. A weld-deposition unit mounted to the CNC for material deposition.

In general, parallel slicing and deposition often can be handled with 2.5-axis. Nevertheless, abrupt overhangs will require at least two additional rotary axes for continuously re-orienting the component for aligning the overhanging feature in-line to the deposition direction. Hence, to obtain the same; a rotary and tilting table is attached to a 2.5-axis vertical machining center, resulting in higher order (5-axis) kinematic movement.

For carrying out the weld-deposition, a synergic cold metal transfer (CMT) equipment is used. CMT is a controlled metal inert gas (MIG) welding process, wherein short circuit mode is predominant over the spray and globular transfer. This can be possible by enabling the push-pull mechanism (around 80 Hz) to the wire instead of only wire supply (push). The push-pull mechanism of weld-deposition unit is responsible for droplet detachment and material transfer without depending exclusively on electromagnetic force. This results in a significant reduction in spatter, heat input and distortion of the workpiece that highlights its suitability for weld-deposition based AM. The experimental setup used for weld-deposition based AM is depicted in Figure 3. The details of the retrofitment of the weld-deposition torch to a CNC both mechanically and electrically is available in the literature and the same was adopted in the present work [16]. For synchronous weld-deposition and milling, the welding machine (CMT) is directly connected to the relay of the CNC so that the welding ON and OFF can be done with the help of CNC (extra M codes which were provided by the machine supplier) without disturbing its actual purpose.

Figure 3: Experimental setup for realizing sudden overhanging features.

The filler wire used in the present work is a copper coated mild steel wire (ER70S-6) with 0.8mm diameter. The shielding gas used for the weld-deposition is Argon + CO_2 mixture in 82% and 18% ratio with a gas flow of 8 litres/min. Earlier studies on ER70S-6 have demonstrated that the mechanical properties like ultimate strength and hardness are comparable or even better than billet of similar composition [33]. Hence, ER70S-6 it a good choice for current metal AM application. As the current study is limited to deposition of sudden overhang features without support structures via weld-deposition based AM, the complete details related to higher order kinematic setup, coordinate transformation, optimal process parameters and its range is not presenting here. The above mentioned technicalities are already explained in-detailed in previous articles and the same has been adopted in the present work [9].

3. Methodology

The current section explains the methodology implemented for the fabrication of components with abrupt overhangs (abrupt is used to refer orthogonal features/overhangs). Such features can be divided into multiple segments. Each segment is of different orientation and a given segment can be realised by 2.5-axis deposition. Hence, an indexed type 5-axis motion i.e., suitable rotation and tilting to orient the given segment vertically, followed by 2.5-axis weld-deposition of that segment. The following sub-sections describe the steps involved to realize the same.

3.1 Adjacency relation between the layers: A sudden or nearly horizontal overhanging feature in a tessellated CAD model is recognized in the current work with the help of adjacency relationship between the layers. Once the CAD model (.stl) is uniformly sliced, based on the relation between two successive layers, layer adjacency can be decided. Figure 4b depicts the same. Let L_n be the circumference loop of the n^{th} slice, L_{n+1} be the circumferential loop of the $(n+1)^{th}$ slice and L'_{n+1} is the projection of L_{n+1} on L_n. If L'_{n+1} is completely inside of L_n, then layer L_{n+1} can be termed to have adjacency relation with L_n. Otherwise L_{n+1} has non-adjacency with respect to L_n.

(a)	(b)	(c)

Figure 4: (a) Input CAD model; (b) Layer adjacency relation between the layers; and (c) Identification of sudden overhangs (n^{th} layer - black colour) using layer adjacency relation.

The layers that have adjacency relation with the previous layer do not require any support for deposition. On the other hand, it is difficult to deposit the non-adjacency layers without the use of supports. Once the layer adjacency with the previous layer is calculated, orthogonal deposition technique (explained subsequently) is used to deposit the non-adjacent layers without supports.

Figure 5 shows the flowchart of the algorithm used for depositing a sudden overhang feature without use of universally acceptable support structures.

Figure 5: Flowchart of the algorithm used for depositing sudden overhanging features without supports.

3.2 Segmentation of the non-adjacent layers: The above depicted algorithm is executed with the help of an in-house MATLAB routine. This MATLAB routine can identify the features with sudden overhangs (Figure 4c) and then sub-divide the overhang features into different segments to be deposited in different tilting directions. The technique starts with giving a CAD model as an input. Once the CAD model is uniformly sliced, the following actions are performed in sequence.

1. Identification of the circumference loop for every sliced layer.
2. Checking layer adjacency or non-adjacency with the previous layer. If the layer adjacency is found, realize that specific layer without orthogonal weld-deposition.
3. If layer adjacency is not found, create a bounding box (BB_n) for the n^{th} layer (L_n).
4. Generation of area-filling tool path for all regions inside the bounding box viz., region (BB_n - L_n) in parallel to the line segment direction.
5. Divide the remaining area (L_{n+1} - BB_n) into a suitable number of regions.
6. Generation orthogonal area-filling tool paths for with user defined layer thickness for all regions i.e., region (L_{n+1} - BB_n).

3.3 Orthogonal weld deposition technique: Though the deposition of a sudden overhang feature without support mechanism is a challenging task in weld-deposition (arc) based AM technique, the same can be realized by an efficient process planning steps (software) in combination of higher order kinematics to the deposition head or to the workpiece (hardware). Although the reported literature in the present article is related to multi-directional deposition, none of them are related with sudden overhang features without supports. The proposed orthogonal weld-deposition technique described in this paper aims to address the same. As mentioned earlier, the experimental setup consists two major systems for precisely positioning the workpiece with defined feed rate and weld-deposition. Hence, to obtain the accurate position a rotary and tilting table (also called as trunnion table) is attached to a 3-axis vertical machining center, resulting in 5-axis kinematic movement. This additional attachment is now feasible to deposit the material in universally acceptable 2.5-Axis deposition (Z-direction) and also along its normal or orthogonal direction. According to this definition, the system proposed is an orthogonal weld-deposition technique for metallic AM.

4. Manufacture Of Sudden Overhanging Features And Illustrative Case Studies

The input and output of the forementioned algorithm are CAD model (.stl file) with layer thickness (t) for slicing and the generated tool path for weld-deposition for various regions in CNC language (G codes and M codes) respectively. The generated tool path is executed in CNC with the synchronous weld-deposition and face milling operation (if necessary) to realize the complex metallic components. To demonstrate capabilities of the above-mentioned algorithm, three case studies with abrupt overhangs have been taken up for deposition. These are carried out with the following weld-deposition parameters: wire feed (W_f)= 5 m/min; torch speed (T_s)= 0.45 m/min and layer thickness (t) = 1.5mm. Initially, the regions inside the bounding box are realized at different inclinations (based on the inclination of each edge with respect to the base of the bounding box) using inclined and/or orthogonal deposition. After that, any two opposite regions (for an example region 5 and region 6 in the case studies) are deposited using orthogonal deposition. By taking the advantage of earlier deposited regions remaining regions (region 7 and region 8) can be realized again in an orthogonal deposition. A important point to be noted in this algorithm is, if the internal contour of the non-adjacent layer itself is a bounding box (case study-2); then the region 1 to region 4 can be omitted and the remaining regions viz. region 5 to region 8 can be realized directly with above explained methodology.

4.1 Illustrative Case study-1: To attest that the above-mentioned algorithm is capable of depositing sudden overhanging features, an illustrative case study as shown in Figure 4a is considered. As may be observed from the Figure 4a, the intended geometry comprises of two parts i.e., a pentagonal base and the circular disc shape at the top. From the sliced data of the CAD model, the layer adjacency rule holds true for the pentagonal base, till layer number 27. Subsequently, there is a sudden change in the layer 28 owing to the abrupt overhang and leading to a non-adjacency condition. To manufacture the same, in the first stage (BB_n - L_n) area is calculated and sub-divided into region 1 to region 4. The workpiece is subsequently oriented in an orthogonal direction for each edge or side of the polygon and then the deposition of the segment connected to that edge is carried out. This process is repeated till the complete is created. In the next stage, the (L_{n+1} - BB_n) area is calculated and divided into four orthogonal regions, region 5 to region 8. Each of these can be then achieved in 0^0, 180^0, 270^0 and 90^0 orientations respectively for creating the final desired shape of L_{n+1} This process may be repeated if more such non-adjacent layers are encountered. Figure 6 and Figure 7 depicts the step by step procedure for segmentation of regions and area-filling respectively for a non-adjacency layer. Figure 8 depicts the execution of the tool path with 5-axis weld-deposition using in in-house MATLAB routine to realize the intended geometry.

4.2 Illustrative case study-2: Another case study (shown in Figure 9a) is subsequently carried out with the above-mentioned weld-deposition parameters (Wf=5.0 m/min; Ts=0.45 m/min and layer thickness = 1.5mm). It may be observed from the sliced data that the intended shape looks like the flange of a coupling and it contains two parts: a square base with a circular disc shape at the top. It is observed from the sliced CAD data that, the layer adjacency rules hold for the square base, till layer 20. Subsequently, there is a sudden change in the layer 21 owing to the overhang and leading to a non-adjacency condition. As described earlier, in the present case the bounding box itself is the inner contour so that the regions inside the BBn can be omitted. In the next stage, the remaining area (Ln+1 - BBn) is calculated and divided into four orthogonal regions such as region 5 to region 8. Each of these can be then achieved in 0^0, 180^0, 270^0 and 90^0 orientations respectively to manufacture a layer with sudden overhanging feature without supports. The segmentation, tool path generation and the final orthogonal weld-deposition for a given non-adjacency layer are showed in-detail in Figure 9.

4.3 Illustrative case study-3: In the present case study, a component similar to the geometry of crank shaft is considered for deposition. The CAD model of the same is depicted in Figure 12a. Similar to the previous case studies, this object also comprises two parts: a cylindrical base with a crank web and repeating at two locations at layer 21 and layer 56. In other words, the layer adjacency relation for the cylindrical shape holds true to layer number 21 and then a sudden overhang of the object led to layer non-adjacency. Similarly, at the second instance, the layer adjacency relation for the cylinder hold true to layer number 56 and then a sudden overhang of the object led to layer non-adjacency. Though the methodology for realizing a sudden overhang is similar, the geometries of the layers are different. Hence, the tool path for these two layers are different and need to be handled separately. However, In the first stage, $(\mathrm{BBn} - \mathrm{Ln})$ area is calculated and sub-divided into four regions let's say region 1 to region 4 for both the cases. To deposit these regions, the workpiece is continuously re-oriented using rotary axis (4^{th} axis). This process continues until the complete bounding box is created. In the next stage, $(\mathrm{L}_{n+1} - \mathrm{BB}_n)$ area is calculated and divided into four orthogonal regions. Region 5 to region 8. Each of these are achieved in 0^0, 180^0, 270^0 and 90^0 orientations respectively to fabricate the sudden overhang. This process can be repeated if more such non-adjacent layers are encountered. The segmentation and tool path generation for two different cases are showed in Figure 10 and Figure 11 separately. Figure 12b represents the final deposited component.

5. Conclusions

A novel methodology for the manufacture of abrupt overhangs without supports meant for metallic AM objects is presented. The process flow chart and the necessary algorithms developed to implement the same have also been discussed in detail. Based on the geometrical complexity, the classification of the objects with the suitable kinematic setup is also presented. The objects with zero and small overhang features can be easily fabricated using 2.5-axis deposition by little over extension from the previous layer. But the objects with large and sudden overhangs demand higher order kinematics (5-axis) for continuous re-orientation. For realizing a sudden overhanging feature without support mechanism, layer adjacency concept, segmentation and orthogonal weld-deposition techniques have been used. An in-house MATLAB routine has also developed and presented to for performing the same. These methodologies have been executed with the help of a GMAW weld-deposition unit for material addition and a 5-Axis (3-linear and 2-rotary) CNC was used for positioning and orientation control. The advantages and capabilities of arc based (GMAW) AM over other metallic AM techniques are also explained. Various case studies are performed to illustrate this novel technique and also presented. Though the technique is illustrated with the help of arc based AM, the algorithms which are developed are generic in nature and are suitable for any other deposition techniques.

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2. ***Conflicts of interest/Competing interests:***

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3. ***Availability of data and material:***

The reported data and the material in the submitted article is original and the same is not submitted anywhere.

4. ***Code availability:***

An In-house MATLAB routine has developed by the authors using licenced MATLAB software.

5. ***Ethics approval:***

Not applicable

6. ***Consent to participate:***

Informed consent was obtained from all individual participants included in the study.

7. ***Consent for publication:***

Patients signed informed consent regarding publishing their data and photographs.

8. ***Authors' contributions:***

Both the authors are equally conceived for the all the activities related to the presented research. Both the authors equally responsible for idea planning, carrying out the experiments, MATLAB code generation and manuscript preparation.

References

[1] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Low cost integration of additive and subtractive processes for hybrid layered manufacturing," *Robot. Comput.-Integr. Manuf.*, vol. 26, no. 5, pp. 490–499, Oct. 2010, doi: 10.1016/j.rcim.2010.03.008.

[2] D. Jafari, T. H. J. Vaneker, and I. Gibson, "Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts," *Mater. Des.*, vol. 202, p. 109471, Apr. 2021, doi: 10.1016/j.matdes.2021.109471.

[3] B. Wu *et al.*, "Mitigation of thermal distortion in wire arc additively manufactured Ti6Al4V part using active interpass cooling," *Sci. Technol. Weld. Join.*, vol. 24, no. 5, pp. 484–494, Jul. 2019, doi: 10.1080/13621718.2019.1580439.

[4] M. P. Sefidi, R. Israr, J. Buhl, and M. Bambach, "Rule-Based Path Identification for Direct Energy Deposition," *Procedia Manuf.*, vol. 47, pp. 1134–1140, Jan. 2020, doi: 10.1016/j.promfg.2020.04.133.

[5] E. R. Denlinger, J. C. Heigel, P. Michaleris, and T. A. Palmer, "Effect of inter-layer dwell time on distortion and residual stress in additive manufacturing of titanium and nickel alloys," *J. Mater. Process. Technol.*, vol. 215, pp. 123–131, Jan. 2015, doi: 10.1016/j.jmatprotec.2014.07.030.

[6] G. d. Janaki Ram, Y. Yang, B. e. Stucker, and C. Robinson, "Use of ultrasonic consolidation for fabrication of multi-material structures," *Rapid Prototyp. J.*, vol. 13, no. 4, pp. 226–235, Aug. 2007, doi: 10.1108/13552540710776179.

[7] R. J. Friel and R. A. Harris, "Ultrasonic Additive Manufacturing – A Hybrid Production Process for Novel Functional Products," *Procedia CIRP*, vol. 6, pp. 35–40, Jan. 2013, doi: 10.1016/j.procir.2013.03.004.

[8] P. L. Blackwell and A. Wisbey, "Laser-aided manufacturing technologies; their application to the near-net shape forming of a high-strength titanium alloy," *J. Mater. Process. Technol.*, vol. 170, no. 1–2, pp. 268–276, Dec. 2005, doi: 10.1016/j.jmatprotec.2005.05.014.

[9] J. S. Panchagnula and S. Simhambhatla, “Manufacture of complex thin-walled metallic objects using weld-deposition based additive manufacturing,” *Robot. Comput.-Integr. Manuf.*, vol. 49, pp. 194–203, Feb. 2018, doi: 10.1016/j.rcim.2017.06.003.

[10] C. Greer *et al.*, “Introduction to the design rules for Metal Big Area Additive Manufacturing,” *Addit. Manuf.*, vol. 27, pp. 159–166, May 2019, doi: 10.1016/j.addma.2019.02.016.

[11] P. Almeida, S. Williams, F. Wang, P. Kazanas, J. Ding, and F. Martina, “Wire plus Arc ALM: Developments for large scale aircraft metal components,” Jan. 01, 2012. [Online].Available: https://www.researchgate.net/publication/51999211_Wire_plus_Arc_ALM_Developments_for_large_scale_aircraft_metal_components

[12] J. J. Penney and W. R. Hamel, “Using non-gravity aligned welding in large scale additive metals manufacturing for building complex parts,” *Solid Free. Fabr. 2019 Proc. 30th Annu. Int. Solid Free. Fabr. Symp. – Addit. Manuf. Conf.*, Jan. 2019, Accessed: Nov. 15, 2021. [Online]. Available: https://par.nsf.gov/biblio/10159186-using-non-gravity-aligned-welding-large-scale-additive-metals-manufacturing-building-complex-parts

[13] Y.-A. Song, S. Park, D. Choi, and H. Jee, “3D welding and milling: Part I–a direct approach for freeform fabrication of metallic prototypes,” *Int. J. Mach. Tools Manuf.*, vol. 45, no. 9, pp. 1057–1062, Jul. 2005, doi: 10.1016/j.ijmachtools.2004.11.021.

[14] Y.-A. Song, S. Park, and S.-W. Chae, “3D welding and milling: part II—optimization of the 3D welding process using an experimental design approach,” *Int. J. Mach. Tools Manuf.*, vol. 45, no. 9, pp. 1063–1069, Jul. 2005, doi: 10.1016/j.ijmachtools.2004.11.022.

[15] R. Dwivedi and R. Kovacevic, “Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding,” *J. Manuf. Syst.*, vol. 23, no. 4, pp. 278–291, 2004, doi: 10.1016/S0278-6125(04)80040-2.

[16] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, “Retrofitment of a CNC machine for hybrid layered manufacturing,” *Int. J. Adv. Manuf. Technol.*, vol. 45, no. 7–8, pp. 690–703, Dec. 2009, doi: 10.1007/s00170-009-2002-2.

[17] Suryakumar Simhambhatla and K.P. Karunakaran, “Build strategies for rapid manufacturing of components of varying complexity,” *Rapid Prototyp. J.*, vol. 21, no. 3, pp. 340–350, Apr. 2015, doi: 10.1108/RPJ-07-2012-0062.

[18] J. D. Spencer, P. M. Dickens, and C. M. Wykes, “Rapid prototyping of metal parts by three-dimensional welding,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 212, no. 3, pp. 175–182, Mar. 1998, doi: 10.1243/0954405981515590.

[19] Y. Zhang, Y. Chen, P. Li, and A. T. Male, “Weld deposition-based rapid prototyping: a preliminary study,” *J. Mater. Process. Technol.*, vol. 135, no. 2–3, pp. 347–357, Apr. 2003, doi: 10.1016/S0924-0136(02)00867-1.

[20] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas, “Design for Wire and Arc Additive Layer Manufacture,” in *Global Product Development*, A. Bernard, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 721–727. Accessed: Jul. 29, 2013. [Online]. Available: https://dspace.lib.cranfield.ac.uk/handle/1826/7349?mode=simple

[21] P. Kazanas, P. Deherkar, P. Almeida, H. Lockett, and S. Williams, “Fabrication of geometrical features using wire and arc additive manufacture,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, p. 0954405412437126, Feb. 2012, doi: 10.1177/0954405412437126.

[22] X. Chen, C. Wang, X. Ye, Y. Xiao, and S. Huang, “Direct Slicing from PowerSHAPE Models for Rapid Prototyping,” *Int. J. Adv. Manuf. Technol.*, vol. 17, no. 7, pp. 543–547, Apr. 2001, doi: 10.1007/s001700170156.

[23] B. Baufeld, O. V. der Biest, and R. Gault, “Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: Microstructure and mechanical properties,” *Mater. Des.*, vol. 31, Supplement 1, pp. S106–S111, Jun. 2010, doi: 10.1016/j.matdes.2009.11.032.

[24] X. Xiong, H. Zhang, and G. Wang, “Metal direct prototyping by using hybrid plasma deposition and milling,” *J. Mater. Process. Technol.*, vol. 209, no. 1, pp. 124–130, Jan. 2009, doi: 10.1016/j.jmatprotec.2008.01.059.

[25] J. S. Panchagnula and S. Simhambhatla, “Additive Manufacturing of Complex Shapes Through Weld-Deposition and Feature Based Slicing,” p. V02AT02A004, Nov. 2015, doi: 10.1115/IMECE2015-51583.

[26] L. Ren, T. Sparks, J. Ruan, and F. Liou, “Process planning strategies for solid freeform fabrication of metal parts,” *J. Manuf. Syst.*, vol. 27, no. 4, pp. 158–165, Oct. 2008, doi: 10.1016/j.jmsy.2009.02.002.

[27] S. McMains, “Double sided layered manufacturing,” 2002. [Online]. Available: https://www.researchgate.net/publication/228577856_Double_sided_layered_manufacturing

[28] R. Dwivedi and R. Kovacevic, “Process Planning for Multi-Directional Laser-Based Direct Metal Deposition,” *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 219, no. 7, pp. 695–707, Jul. 2005, doi: 10.1243/095440605X31535.

[29] Y. Ding, R. Dwivedi, and R. Kovacevic, “Process planning for 8-axis robotized laser-based direct metal deposition system: A case on building revolved part,” *Robot. Comput.-Integr. Manuf.*, vol. 44, pp. 67–76, Apr. 2017, doi: 10.1016/j.rcim.2016.08.008.

[30] F. Liou, K. Slattery, M. Kinsella, J. Newkirk, H.-N. Chou, and R. Landers, “Applications of a hybrid manufacturing process for fabrication of metallic structures,” *Rapid Prototyp. J.*, vol. 13, no. 4, pp. 236–244, Aug. 2007, doi: 10.1108/13552540710776188.

[31] Y. Chen, C. Zhou, and J. Lao, “A layerless additive manufacturing process based on CNC accumulation,” *Rapid Prototyp. J.*, vol. 17, no. 3, pp. 218–227, 2011, doi: 10.1108/13552541111124806.

[32] J. Panchagnula and S. Simhambhatla, “Inclined Slicing and Weld-Deposition for Additive Manufacturing of Metallic Objects with Large Overhangs using Higher Order Kinematics.,” *Virtual Phys. Prototyp.*, doi: 10.1080/17452759.2016.1163766.

[33] S. Suryakumar, K. P. Karunakaran, U. Chandrasekhar, and M. A. Somashekara, “A study of the mechanical properties of objects built through weld-deposition,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 227, no. 8, pp. 1138–1147, Aug. 2013, doi: 10.1177/0954405413482122.

Figures

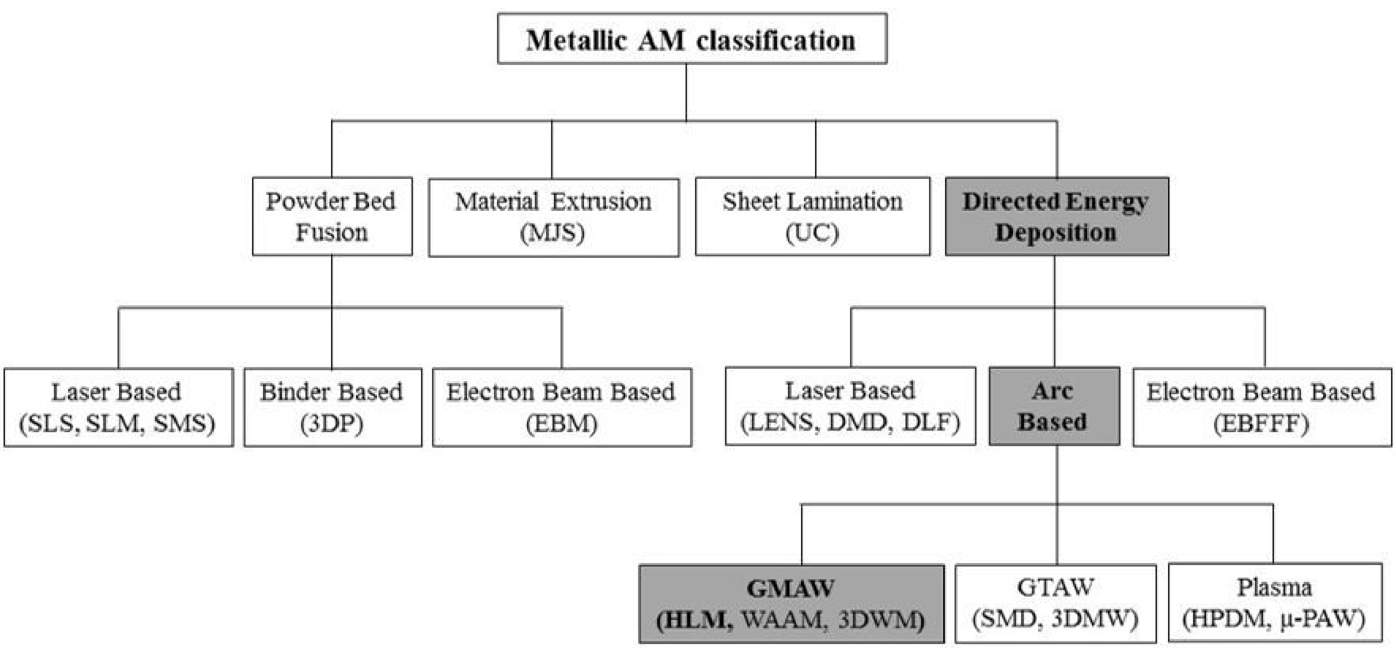


Figure 1

Broad classification of metallic AM techniques available.

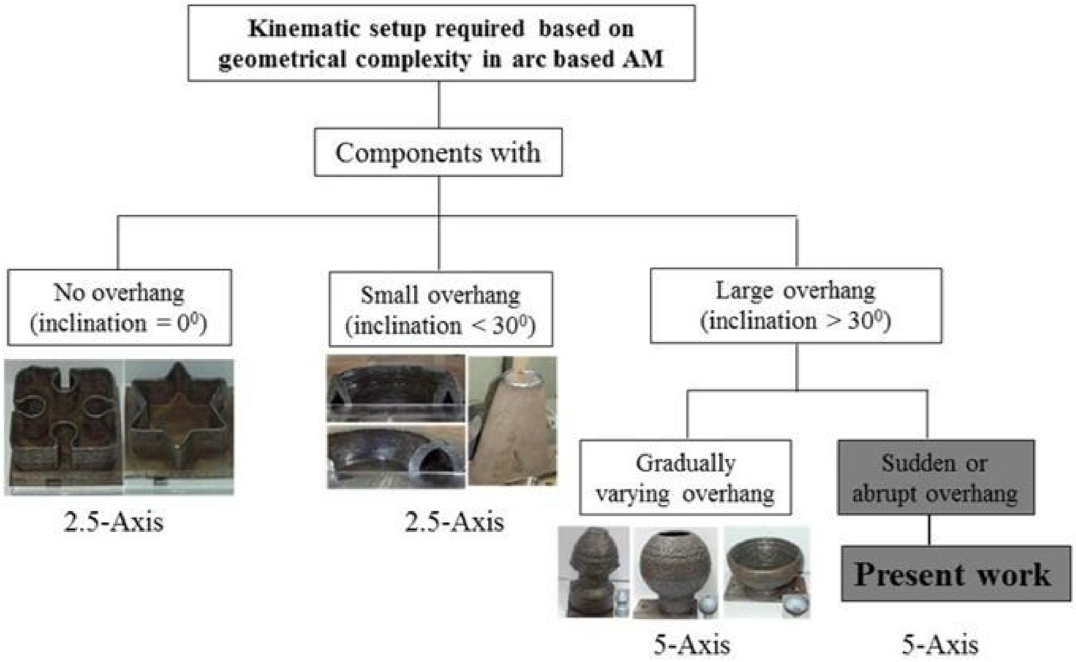


Figure 2

Various kinematic setups required for arc based AM.

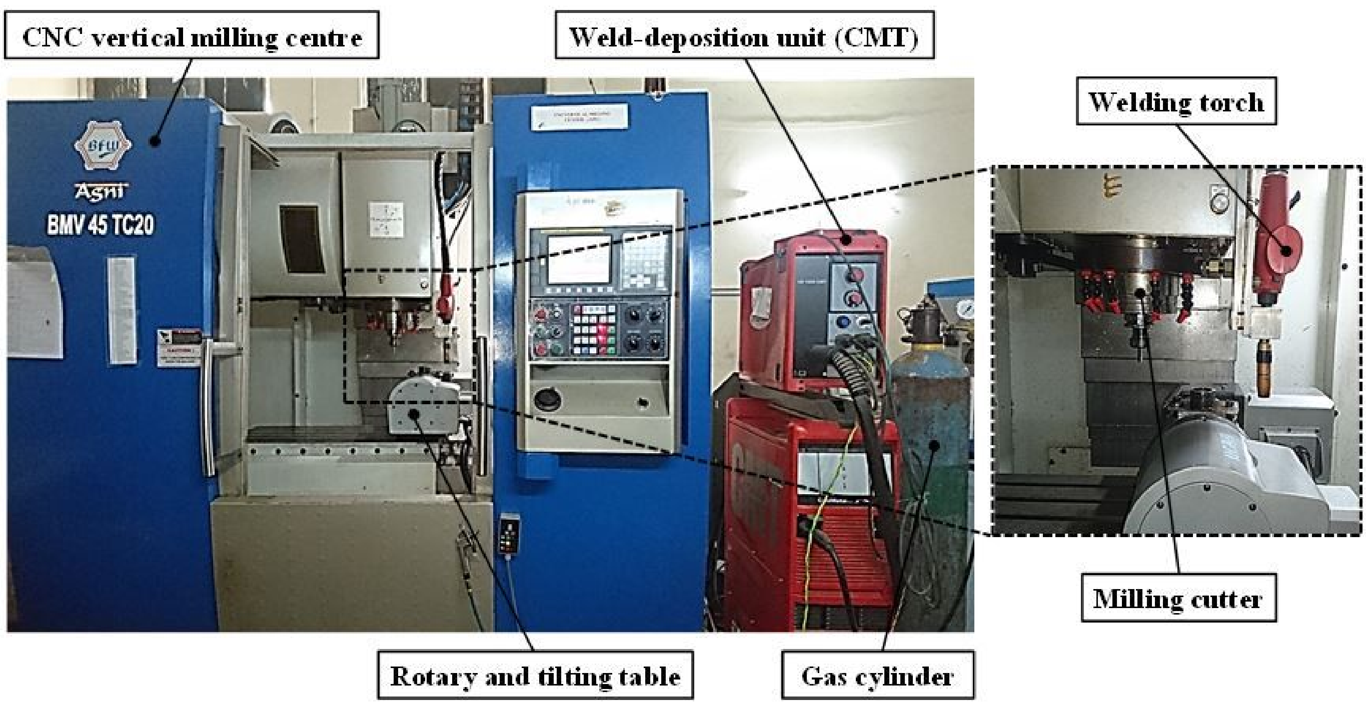


Figure 3

Experimental setup for realizing sudden overhanging features.

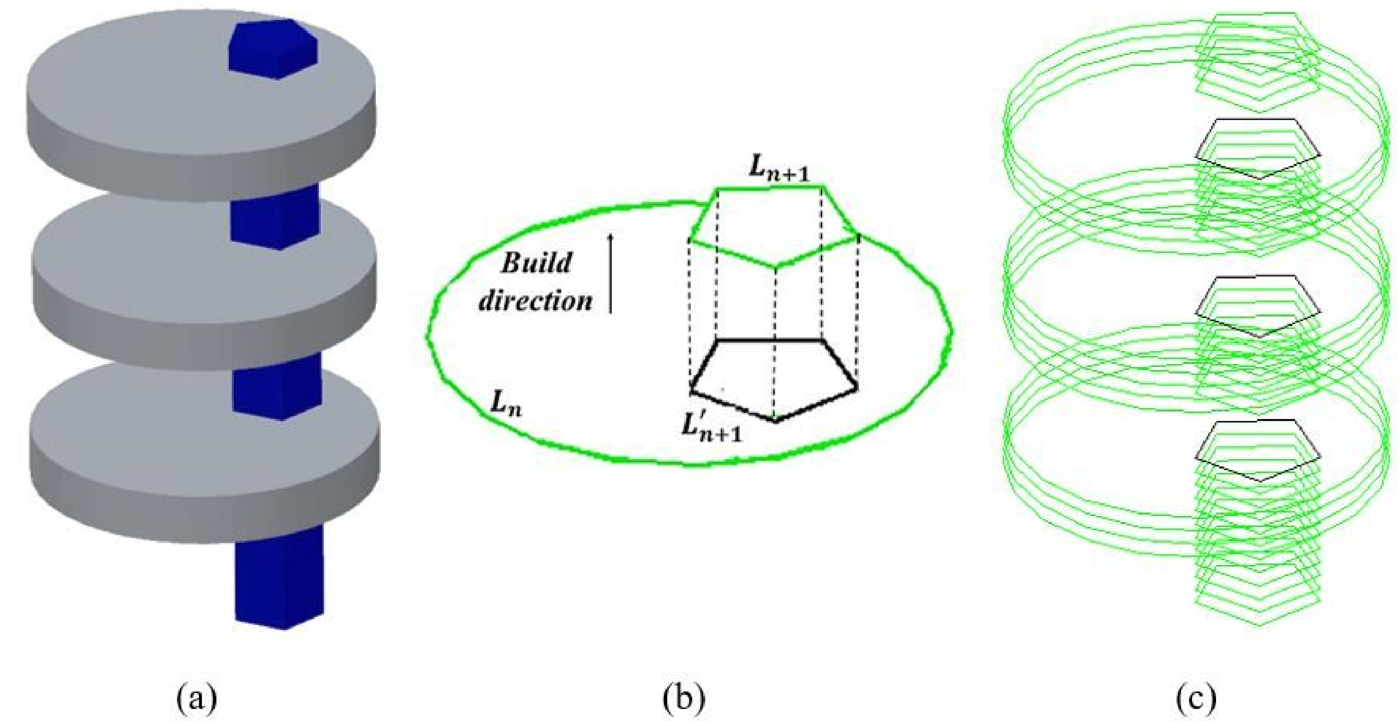


Figure 4

(a) Input CAD model; (b) Layer adjacency relation between the layers; and (c) Identification of sudden overhangs (nth layer - black colour) using layer adjacency relation.

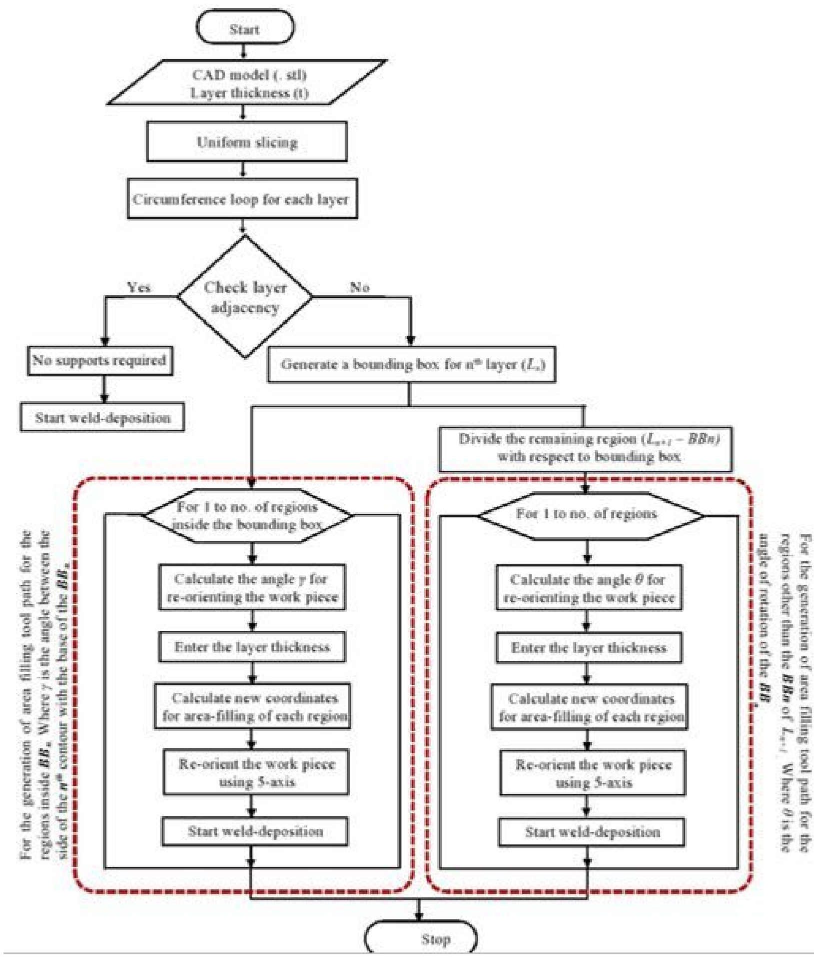


Figure 5

Flowchart of the algorithm used for depositing sudden overhanging features without supports.

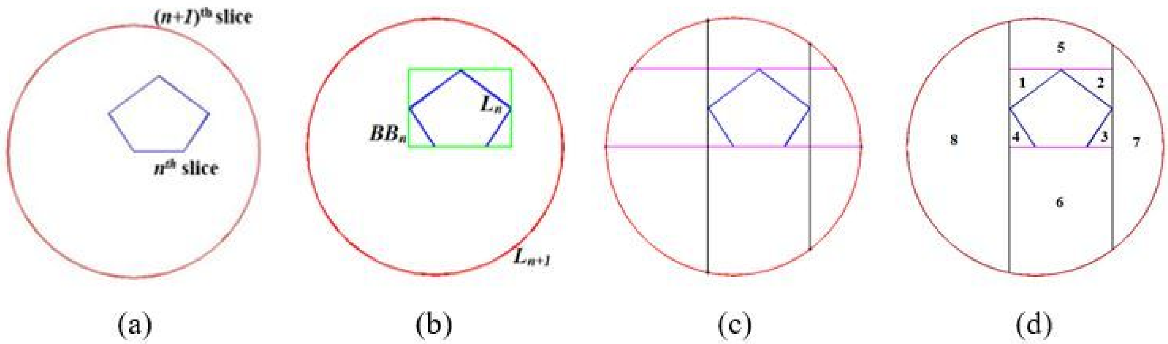


Figure 6

Segmentation and regions creation for the non-adjacent layer: (a) Two different contours red - (n+1)th slice and blue -nth slice; (b) Bounding Box (BBn) creation; (c) Dividing remaining area into regions based on BBn; (d) Regions (region 1 to region 8) to be deposited.

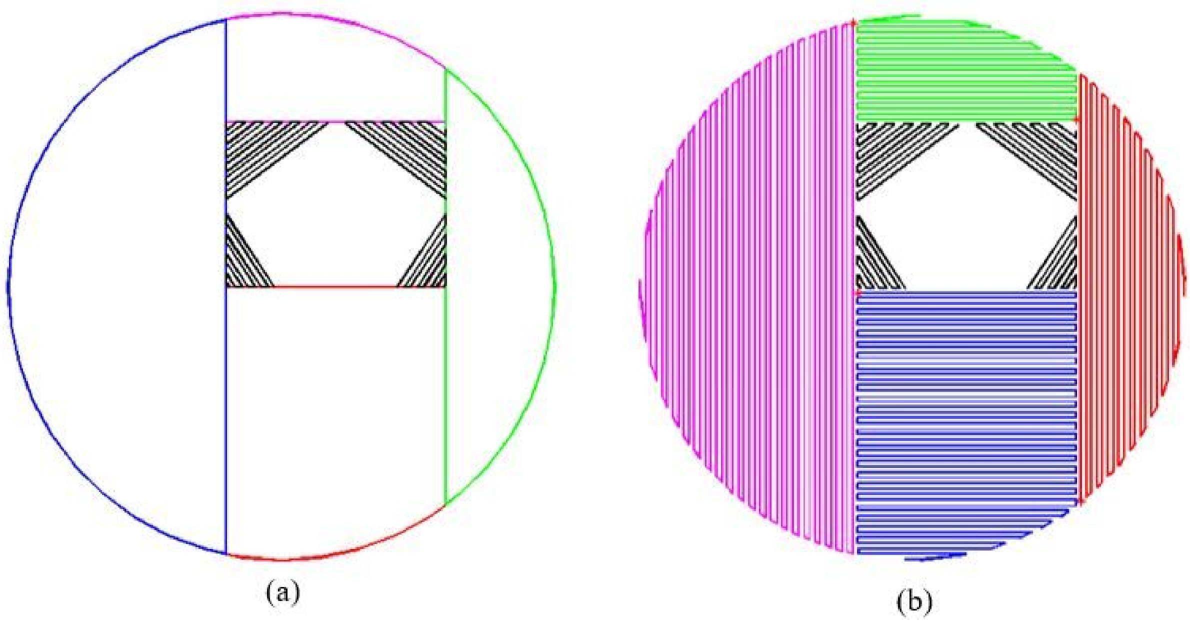


Figure 7

Tool path generation for various regions using in-house developed MATLAB routine : (a) For the regions inside the Bounding Box (BBn); (b) For the regions other than the Bounding Box i.e. (Ln+1 - BBn).

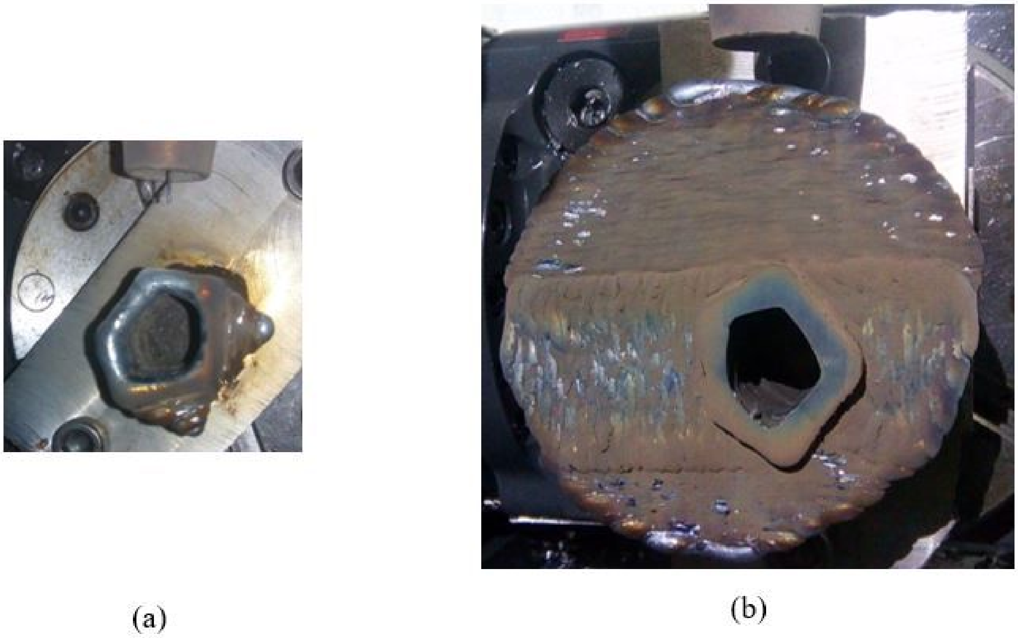


Figure 8

Execution of tool path using 5-axis weld-deposition: (a) Deposition of regions inside the bounding box i.e., region 1 to region 4; (b) Orthogonal deposition to complete the layer Ln+1 i.e., region 5 to region 8.

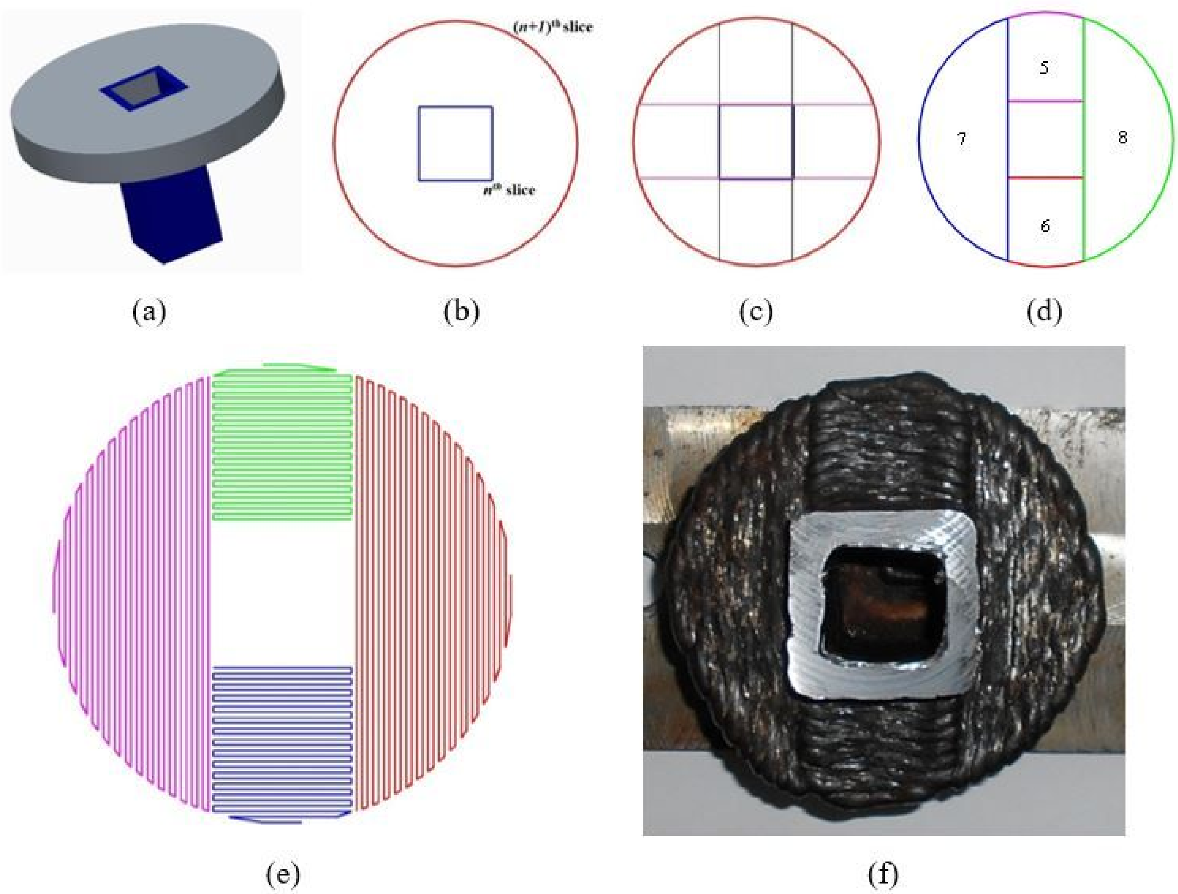


Figure 9

(a) CAD model; (b) Two different contours red - (n+1)th slice and blue -nth slice; (c) Dividing entire area into regions based on BBn; (d) Regions (region 5 to region 8) to be deposited; (e) Tool path generation; and (f) Final deposited component.

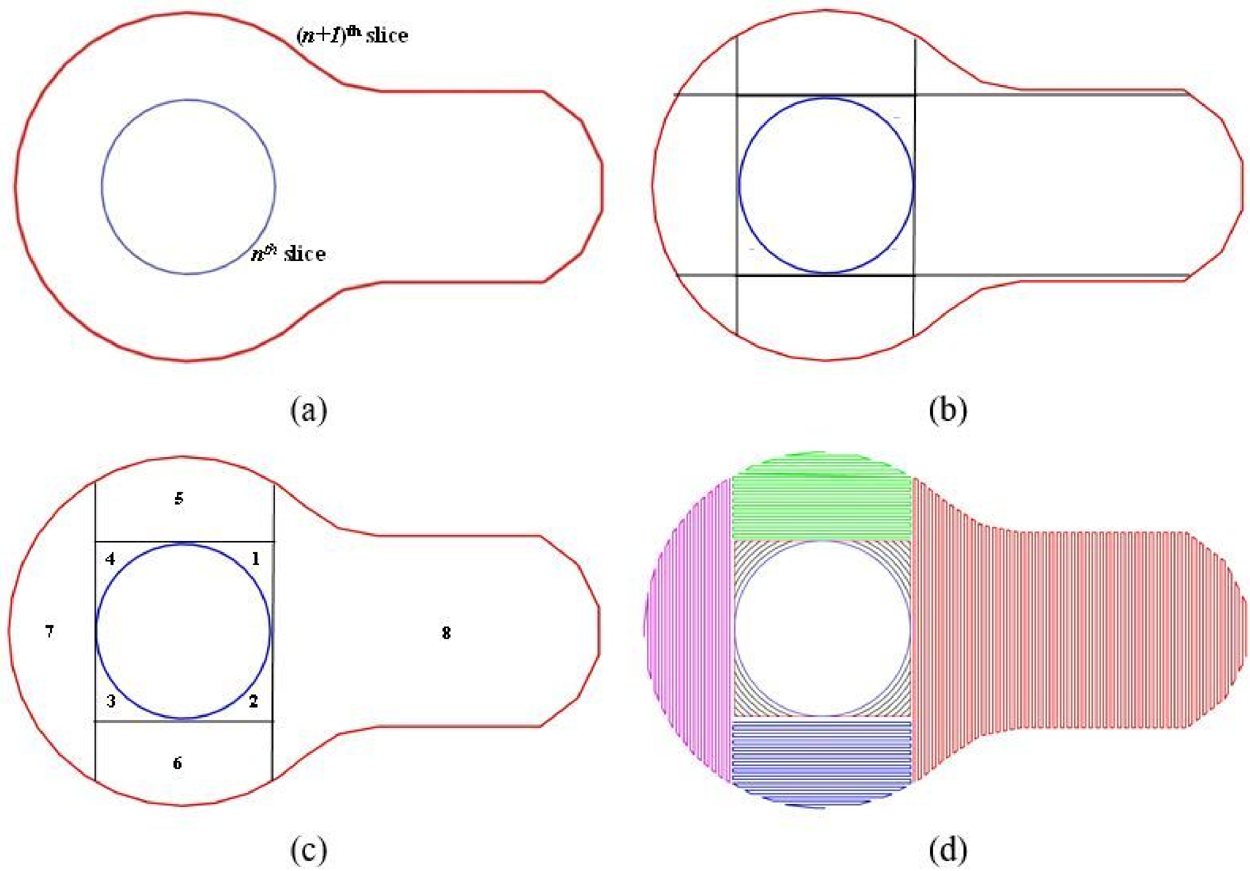


Figure 10

(a) Two different contours red - (n+1)th slice & blue -nth slice; (b) Bounding box creation; (c) Non-adjacent layer segmentation; and (d) Tool path generation using in-house MATLAB routine.

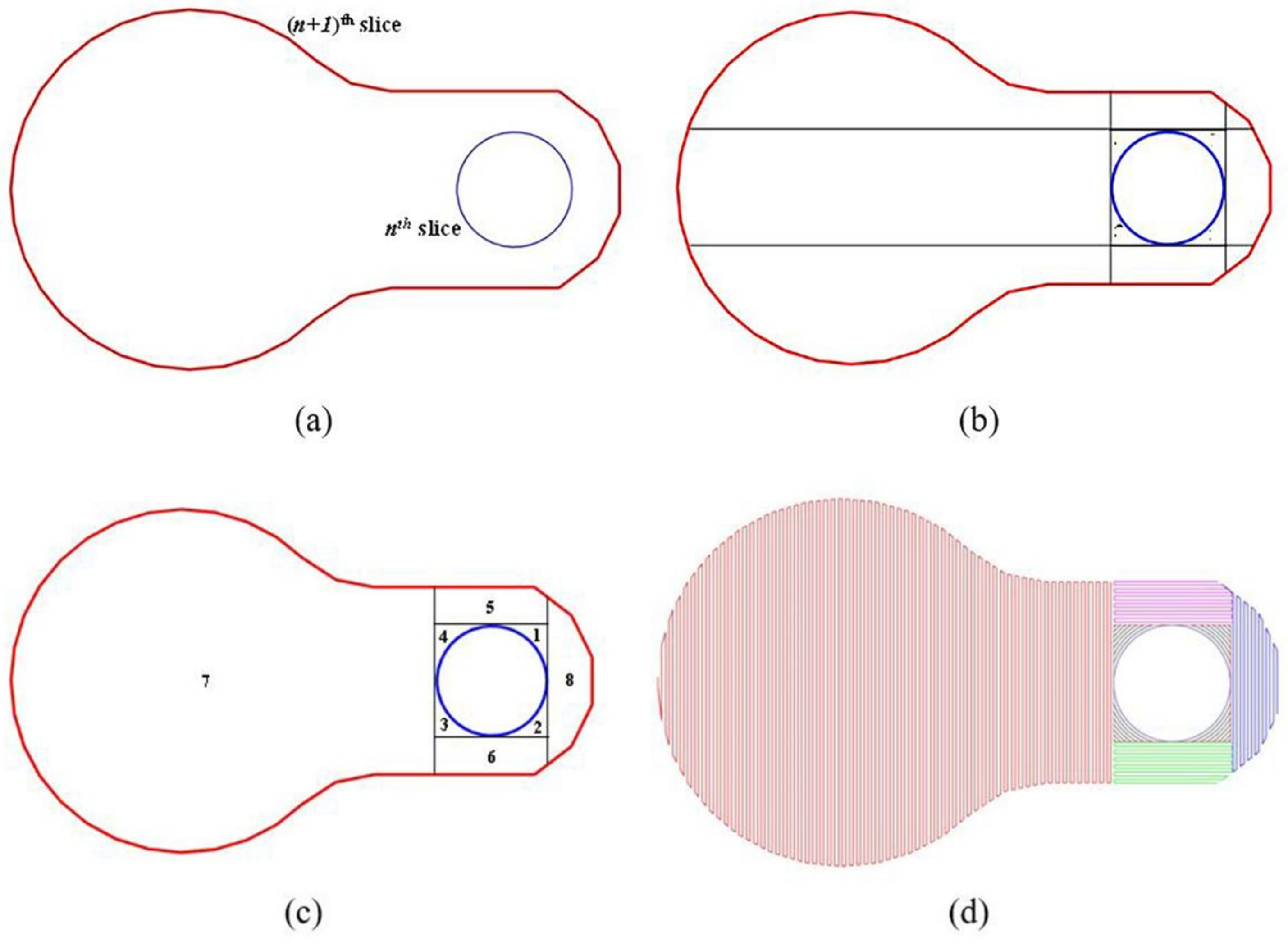
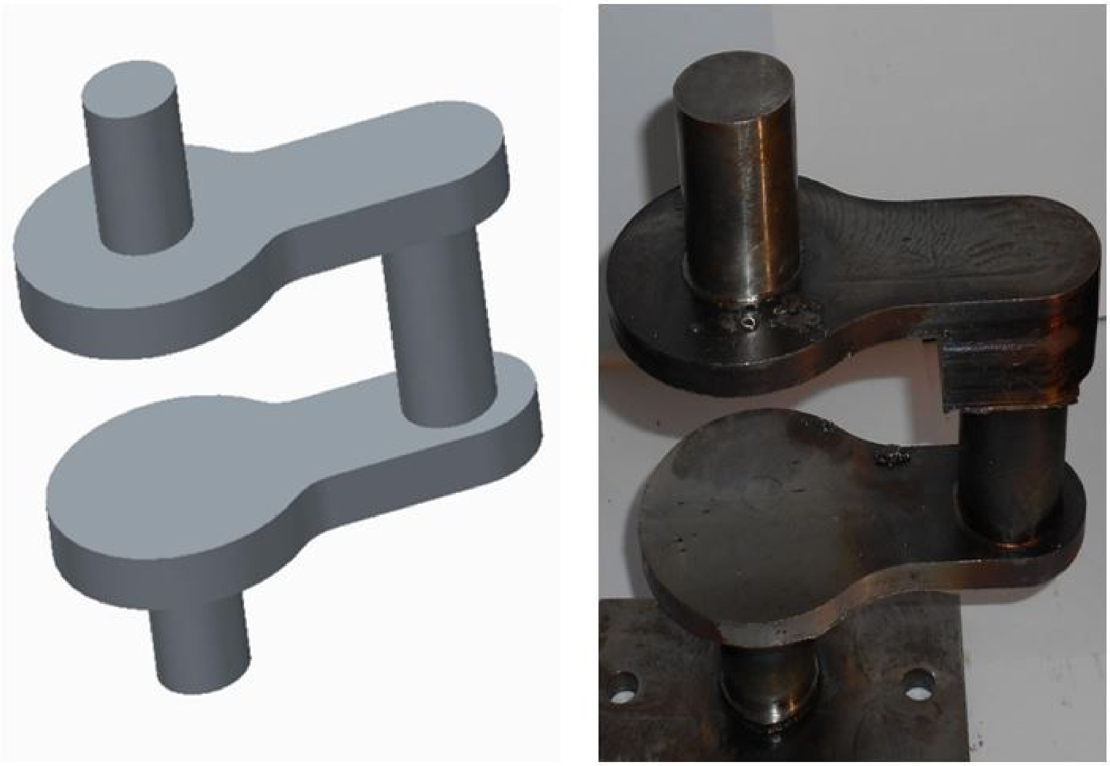


Figure 11

(a) Two different contours red - (n+1)th slice & blue -nth slice; (b) Bounding box creation; (c) Non-adjacent layer segmentation; and (d) Tool path generation using in-house MATLAB routine.



(a) (b)

Figure 12

(a) CAD model; and (b) Final weld-deposited component.