Research Status of the Influence of Cross Multi axis Printing and Material Properties on the Stepped Effect

Xuan Zhuo

{2023010482@bistu.edu.cn}

School of Instrumentation Science and Opto-electronics Engineering, Beijing Information Science & Technology University, Beijing, 100000, China

Abstract. Under the background of accelerating the upgrading of the high-end manufacturing industry to precision and customization, the requirements for surface accuracy of parts in key fields such as aerospace, medical devices, and precision instruments continue to rise. However, as an inevitable inherent defect in the additive manufacturing process, the step effect not only directly affects the appearance quality of parts, but also reduces the mechanical properties and assembly accuracy, significantly increases the cost of subsequent polishing and other post-processing, and severely restricts the large-scale application of additive manufacturing technology in high-precision scenes. In order to solve the restriction of stepped effect on the surface accuracy of printed parts in additive manufacturing, this paper systematically reviews the research status of the influence of multi axis printing and material properties on stepped effect. Firstly, the formation principle and detection method of the step effect are described. Then, the inhibition effect of multi axis printing on the step effect is analyzed from three aspects: equipment configuration, layered path planning, and process parameter regulation. Then, the influence mechanism of material thermophysical, rheological, and solidification properties on the step effect is discussed. Finally, the synergy between multi axis printing and material properties is studied, such as multi axis dynamic adjustment of thermophysical properties of adaptive materials to reduce step defects, matching rheological properties to improve gap filling effect, etc.

Keywords: Multi axis printing, Ladder effect, Material properties, Surface roughness, Process parameters.

1 Introduction

With the rapid upgrading of high-end manufacturing industry, aerospace, medical devices, precision equipment and other fields have increasingly stringent requirements on the surface accuracy of parts. Additive manufacturing technology has become the core support of high-end product development and production by virtue of the advantages of complex structure forming, but the surface roughness problem caused by the ladder effect seriously restricts its application in high-precision scenes. The stacking cumulative error of traditional three-axis printing leads to the formation of obvious stepped defects on the surface of complex curved parts, which not

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only affects the appearance quality of products, but also reduces the mechanical properties and assembly accuracy, and increases the cost of post-processing [1]. To solve the problem of ladder effect and improve the surface accuracy of printed parts has become a key issue to promote the high-end and industrialization of additive manufacturing technology, which has important practical significance to break through the bottleneck of high-end manufacturing.

In recent years, additive manufacturing technology has made significant progress in equipment upgrading and material innovation. The multi axis printing technology has gradually replaced the traditional three-axis equipment. The 3+2-axis, five axis printing equipment and 6-DOF manipulator configuration rely on redundant degrees of freedom to weaken the ladder effect by dynamically adjusting the nozzle posture. Some hybrid manufacturing equipment combined with the alternating process of increasing and decreasing materials has realized the direct elimination of the ladder structure [2,3]. In the field of materials, PLA based gradient composites, Ti-6Al-4V alloy and other new materials are constantly emerging, which have both processability and performance adjustability, providing new possibilities for optimizing the molding quality [4]. At the same time, the development of non planar layering strategy, dynamic process parameter regulation and other technologies has further enriched the means of restraining the ladder effect. However, there are still obvious shortcomings in the current research, such as insufficient matching between multi-axis motion trajectory and material rheological properties, unclear interface bonding and step repair mechanism of new materials in multi-axis printing, imperfect collaborative optimization system of equipment, process and materials, and great room for improvement in the inhibition effect of step effect.

This study focuses on the influence of multi axis printing and material properties on the step effect in detail. Firstly, the formation principle of the step effect was described, and the key influencing factors such as the delamination thickness and the surface angle of the model and their quantitative relationship were clarified. Then, the mainstream detection methods such as surface morphology observation and quantitative parameter measurement were combed. Then, the inhibition mechanism of multi axis printing on the step effect was analyzed from three aspects: equipment configuration, delamination and path planning, and dynamic control of process parameters. Then, the effects of material thermophysical properties, rheological properties, and solidification properties on the formation and severity of the step effect were discussed by affecting melting, flow, and solidification behaviors. Finally, the synergy between multi axis printing and material properties was studied, including reducing defects by dynamically adapting thermophysical properties, improving gap filling effect by matching rheological properties, and optimizing delamination and path strategies by combining solidification properties, The aim is to construct the theoretical framework of multi axis printing and material collaborative optimization, and to provide theoretical and engineering reference for weakening the ladder effect and improving the surface accuracy of prints.

2 Formation principle and detection method of ladder effect

2.1 Formation principle

Ladder effect is a common surface defect in 3D printing (additive manufacturing), and its core cause is the forming essence of layer by layer accumulation. The traditional 3-axis (including 2.5-Axis) printing uses the plane layering method along the fixed direction, which discretizes the complex model into parallel plane slices. There is a height difference between adjacent slices, and the "ladder" discontinuous morphology is formed after the material is superimposed. The severity is related to the thickness of the layer and the angle of the model surface. The greater the layer thickness, the smoother the surface slope, and the more obvious the effect, and the lower surface is usually more significant than the upper surface. The specific influencing factors include: nozzle diameter, layer thickness of the system, angle of the molding direction of the model, etc. In addition, this effect will be coupled with other surface defects such as spheroidization effect and spatter particle adhesion, which will also be exacerbated by insufficient material extrusion, too short solidification time, and asynchronous z-axis movement and nozzle extrusion.

2.2 Test method

The following methods are commonly used to detect the ladder effect.

The first method is the comparative observation method of surface morphology, which visually compares the surface morphology of parts under different process conditions by means of scanning electron microscope (SEM) and other microscopic observation methods, so as to judge the reduction degree of step error. At the same time, with the help of three-dimensional reconstruction technology, the three-dimensional scanning thermal map of the surface is generated, through which the layered structure and depression of the surface of parts are compared.

The second is the quantitative parameter measurement method. The confocal microscope can accurately measure the three-dimensional morphology of the part surface, and then quantify the height and spacing of the steps [5]. The surface linear contour data can be obtained by using the laser profilometer, and the roughness parameters such as arithmetic average roughness (RA), three-dimensional roughness (SA) can be calculated based on these data [5]. In addition, quantitative indicators such as arithmetic mean roughness (RA) and three-dimensional roughness (SA) can also be directly determined by the roughness tester [5].

The third is the model comparison and verification method. First, the simplified models such as cone, semi-circular sphere and cone are designed, and then these models are printed according to different parameter groups. After printing, the actual step height of the model is measured and compared with the theoretical calculation value [2,4].

The fourth is the simulation and simulation method, which uses professional software such as repeater host to visualize the print path, and observe the discrete stepped stripes at the surface contour through the visualization results [6].

Finally, for the error measurement method, first define the maximum distance between the actual surface and the ideal surface at a specific height, and then quantify the degree of step effect by comparing the deviation values of different height measurement positions [6].

3 Influence of multi axis printing on ladder effect

3.1 Influence of equipment configuration

The 3+2 axis printing equipment can achieve high-efficiency adaptation to low and medium complexity curved parts while ensuring printing stability through the combined movement of fixed rotating workbench and XYZ axis. Its structural characteristics enable it to effectively reduce the step error under the premise of taking into account the processing efficiency, especially suitable for scenes where there is a balance between accuracy and efficiency in batch production.

With the flexible linkage of the double rotating shafts, the five axis printing equipment can realize the precise attitude adjustment of the nozzle at various parts of the complex surface, and can minimize the deviation between the plane layering and the design surface. It has a more significant inhibition effect on the stepped effect of high curvature and special-shaped structural parts, but has higher requirements on the equipment calibration accuracy and operation professionalism.

The 6-DOF manipulator has the ability of ultra-high degree of freedom space movement, which can break through the movement limitations of traditional machine tools, adapt to various extremely complex part structures, and realize the precise control of ladder effect through flexible attitude adjustment. However, its motion trajectory planning is difficult, and it needs to be combined with special algorithms to ensure the stability and accuracy of printing.

The dual turntable configuration cooperates with the spindle movement through the bidirectional rotation of the workbench, which can always maintain the optimal forming angle during the printing process, reduce the step bulge caused by the dislocation between layers, and has strong structural rigidity, which is suitable for the processing of large-size and high-precision parts. The parallel arm configuration has the advantages of compact structure layout and fast dynamic response ability. It can adjust the nozzle position through multi arm coordination, quickly adapt to the surface changes of parts, and shorten the printing cycle. However, it is slightly less flexible in handling large stroke printing tasks [3].

3.2 Impact of layering and path planning

The non planar layering strategy breaks the inherent limitations of traditional planar layering by using surface layering methods such as parametric surface offset, micro bending slicing, spiral slicing, and the hybrid layering method of surface layering in high curvature areas and plane layering in other areas, so that the slice layer can closely fit the model surface, thus effectively reducing the discretization error in the additive manufacturing process from the source [1,3,6].

The path planning optimization work will generate three-dimensional spatial paths through dynamic TAD (tool axis) strategy, multi TAD combination strategy, spatial mapping method, contour parallel path method, geodesic method and other methods. At the same time, the path smoothing strategy such as Gaussian hemisphere interpolation will be used to reduce the sudden change of the direction of the deposition head, and the nozzle direction will be adjusted for different types of surfaces, such as making the nozzle direction of the high curvature upper surface coincide with the normal, and aligning the nozzle direction of the suspension structure with the tangent, so as to improve the path adaptability [1,7,8].

Model and process optimization is to decompose the model into unsupported components through the branch_partition process, and then reasonably plan the printing order of each component in combination with the hierarchy_build process. At the same time, with the help of the modified branch_partition algorithm, the effect of stacking between layers is further optimized to ensure the stable connection between layers [9].

3.3 Optimization effect of dynamic control of process parameters on ladder effect

In the dynamic control of process parameters, the adaptive control of layer thickness is the key means to optimize the ladder effect, which needs to be dynamically adjusted according to the surface curvature of the model. For high curvature areas, thinner layer thickness is used to reduce the discretization error. At the same time, the slice parameter set is generated recursively by dichotomy, and the maximum layer thickness is reasonably set to ensure that the layer thickness adjustment meets the accuracy requirements and takes into account the printing efficiency [3,7,9].

The control of printing direction and posture should be based on the tangent vector of the skeleton curve to determine the dynamic printing direction, accurately adjust the angle between the nozzle and the part surface to make it in the normal or tangent direction, and dynamically optimize the printing posture angle to ensure that the extrusion head is always vertical to the part surface in the printing process, so as to reduce the interlayer deviation [1,7,9].

In addition, the ladder effect can be further weakened by optimizing a number of other process parameters, such as adjusting energy density (such as lpbf process), scanning speed and parameters related to molten pool stability, adjusting scanning strategy (such as hatch distance) and path overlap rate, setting appropriate safe moving height, adopting surface remelting process and variable velocity deposition method, and matching 100% filling density and other parameters, so as to comprehensively improve the surface quality of printed parts [5].

4 Influence of material properties on ladder effect

Material properties, including thermophysical properties, rheological properties, and solidification properties, directly determine the formation and severity of the step effect by affecting the melting, flow, and solidification behavior of materials during 3D printing.

4.1 Influence of thermophysical properties

The thermal conductivity, thermal expansion coefficient, melting point and specific heat capacity of the material affect the temperature distribution and thermal deformation during the molding process. The solidification of molten pool of materials with moderate thermal conductivity (such as Ti-6Al-4V) is more controllable, and the ladder effect is relatively mild. Poor thermal conductivity will lead to local temperature accumulation, affecting the solidification consistency. When the coefficient of thermal expansion is too large or the thermal conductivity is uneven, the interlayer cooling shrinkage is uneven, which will aggravate the stepped texture and gap [3]. The effect of thermophysical properties of materials on the step effect can be directly reflected through the control of process parameters such as printing temperature and ambient temperature. For example, PLA materials are selected as the object, and the key parameter range is determined in combination with its thermophysical properties: the optimal printing temperature range of PLA is 180~220 ℃, which can ensure the full melting of materials and maintain appropriate fluidity, and avoid excessive rheology caused by insufficient interlayer bonding or excessive temperature due to too low temperature; The results show that the ambient temperature of 40~50 ℃ can prolong the incomplete plasticization time of the material, slow down the solidification rate of the molten material, provide a more sufficient time window for its flow and filling at the step gap, and weaken the formation of the step structure; At the same time, the optimal printing speed range of PLA is 40~100 mm/s, which is matched with the conventional layer height (0.1mm) of self-supporting inclined plane printing. Through the adaptation of thermophysical properties and process parameters, we can further explore the regulation law of material melting, flow and solidification process on the severity of ladder effect. In addition, Zn and other materials with excellent wettability are prone to uncontrolled lateral movement of the molten pool, resulting in uneven interlayer connection and aggravating the effect [5].

4.2 Influence of rheological properties on ladder effect

The viscosity, fluidity and adhesion of materials directly affect the quality of deposition molding. Low viscosity materials are easy to spread but may overflow, and the ladder effect is "gentle wavy". The spread of high viscosity materials is limited, and the height difference between layers is obvious. The effect is more prominent. Insufficient adhesion will lead to interlayer separation and aggravate the ladder effect. Taking the FDM process as an example, poor rheological properties will lead to irregular stacking shape of printing wires (such as symmetrical track shape), which is difficult to form a uniform layer, making the effect more obvious [1,3,10]. uneven interlayer connection and aggravating the effect [5].

4.3 Influence of solidification characteristics on step effect

The solidification rate, solidification shrinkage and crystalline morphology of the material affect the interlayer bonding quality. Too fast solidification speed will lead to insufficient interlayer bonding, more obvious stepped boundary, and too slow solidification speed may lead to sagging phenomenon. The material with large solidification shrinkage is easy to form tiny gaps between layers, which aggravates the step effect. The material with fine crystal solidification has a denser interlayer bonding, which can reduce the significant degree of effect. For example, in the process of self-supporting inclined plane printing, when the material is in the fully solidified state, the previous layer of material has been completely solidified and formed, and the molten material of the subsequent printing layer is difficult to flow to the stepped gap, and it is easy to form an obvious stepped structure between layers, resulting in the increase of surface roughness. When the material is in the incompletely solidified state, the previous layer of material still maintains a certain plasticizing fluidity, and the molten material of subsequent printing can be filled and spread to the stepped gap with the help of its own rheological properties and the interface bonding force of the incompletely solidified layer, so as to weaken the bulge degree of the stepped structure. The essence of this difference in solidification state is the matching relationship between material solidification rate and printing rhythm. The crystal growth direction will also affect the consistency of interlayer structure, and then correlate the performance of ladder effect [3,6].

5 Influence of multi axis printing and material properties

5.1 Collaborative suppression of multi axis printing and material thermophysical properties

Multi axis printing can effectively disperse the heat of molten pool and adapt to the thermal deformation law of materials through dynamic direction adjustment. For high thermal conductivity materials, it can reduce the uneven flow of molten pool caused by local overheating. For high expansion coefficient materials, it can optimize the direction of printing path to reduce the interlaminar dislocation caused by thermal deformation, while for materials with good thermal stability such as PLA, it can reduce the difference of interlaminar thermal deformation, and then reduce the thermal stress cracking and gap at the step [1,5,10].

5.2 Collaborative optimization of multi axis printing and material rheological properties

Multi axis printing can adapt the rheological properties of different materials by adjusting the nozzle posture, motion speed, feed speed, path spacing and curvature. For high viscosity materials, the layer thickness will be reduced and the offset speed will be reduced to avoid the accumulation problem. For low viscosity materials, the single deposition thickness will be reduced and the path overlap rate will be adjusted to make up for the defects of easy flow. At the same time, the extrusion parameters will be optimized combined with the rheological properties of materials to make the materials more suitable for the surface layered path.

5.3 Synergistic weakening of multi axis printing and material solidification characteristics

The layering strategy, path planning and posture adjustment of multi axis printing can accurately match the solidification characteristics of materials. For high shrinkage materials, multi axis thin-layer deposition is used to fully integrate the interlayer materials. For materials with fast solidification speed, Euler loop diameter and other continuous paths are selected to reduce the uneven solidification caused by printing interruption. For materials with slow solidification speed, the printing posture angle will be dynamically adjusted to ensure the stability of the center of gravity of the deposition layer. When combined with the material reduction process, the surface layer formed after solidification can be accurately milled to eliminate the step error.

6 Conclusion

This study elaborates the influence of multi axis printing and material properties on the step effect of additive manufacturing. It is clear that the ladder effect is caused by layer by layer stacking and can be detected by morphology observation and parameter measurement due to the influence of layer thickness and model angle. The inhibition effect of multi axis printing on ladder effect is analyzed from three aspects: equipment configuration, hierarchical path planning and process parameter regulation. The influence mechanism of thermophysical, rheological and solidification properties of materials on the step effect is described. Finally, it is pointed out that the synergy of multi axis printing and material properties can further weaken the ladder effect through dynamic adaptation and parameter optimization, which provides theoretical and engineering reference for related research.

In the future, in-depth research on 3D printing for multi axis and material properties can be carried out from five core dimensions. The first is to deepen the research on the adaptability of new materials such as superalloys and functional gradient materials to multi axis printing, and build the correlation model of material properties, printing parameters and step effect inhibition effect, so as to provide theoretical support for process optimization. The second point is to develop an AI driven intelligent collaborative optimization system to further improve the suppression accuracy of the ladder effect through real-time dynamic adjustment of printing parameters. The third point is to explore the influence mechanism of temperature field, stress field and other multi field coupling effects on the synergistic inhibition of the ladder effect, and clarify its internal law of action; The fourth point is to innovate the multi axis additive and subtractive composite process and green post-treatment technology to achieve the efficient elimination of the ladder effect, taking into account the processing efficiency and environmental protection needs. Finally, it is necessary to break through the bottleneck of multi axis printing of complex shaped parts and formulate customized processing scheme to meet the stringent requirements of parts accuracy in the high-end manufacturing field.

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