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Analysis on Common Manufacturing Defects and Related Issues of Lattice Structures in 3D Printing

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Abstract: Lattice structures have been used to construct some of the light-weight, high-surface-area and mechanically-adaptable parts of additive manufacturing. However, the complex shape of these parts is also more prone to manufacturing defects such as porosity, lack of fusion, dimensional deviation, strut waviness, surface roughness and poor interlayer bonding. This paper introduces the main kinds of defects in 3D-printed lattice structures and analyzes the problems they cause to the mechanical properties, fatigue life and design reliability of such structures. Many of the lattice failures have been caused by the combined effect of geometry, process parameters and material behaviour during printing, not by design problems alone. According to the latest research on defect characterization, numerical modelling and machine learning for defect reduction have been applied to pinpointing frequent production problems and their expanded influence on quality control and structural performance. Therefore, to obtain defect-free lattice structures, integrated control at all stages of design, process supervision and post-processing is needed, and a single solution is insufficient.

Keywords: Additive manufacturing, lattice structures, manufacturing defects, porosity, lack of fusion, dimensional accuracy.

1. Introduction

3D Printing can produce a lattice structure with an irregular interior that is difficult to get otherwise. The above structures are often used in the aerospace industry, medical devices, energy-absorbing systems and lightweight engineering because they have good strength-to-weight ratios and adjustable mechanical properties [1-2]. Lattices have a relatively complicated shape and are also more susceptible to damage during printing.

Research in recent years has found that lattice structures often have defects such as strut waviness, thickness variation, internal voids, contour plurality, and surface roughness; all of these can reduce the compressive strength and change the deformation behavior of the structure [1, 3]. Some of the defects are caused by slicing and toolpath limitations; others are due to poor layer fusion, insufficient energy input or powder-related irregularities. Performance prediction for lattice structures is often based on ideal geometry, so manufacturing defects cause a discrepancy between the theoretical design and the actual printed behaviour [4, 5].

First, we will introduce some representative defects of 3D-printed lattice structures and the problems they cause in practice. First, the main types of defects will be introduced; next, the mechanical and quality-control problems caused by these defects will be discussed; finally, new directions for reducing defects, such as design optimisation, computed tomography, numerical modelling and machine learning, will be considered. This paper aims to list the production problems of printed lattices that limit their reliability and the corresponding counter-measures taken.

2. Defect Categories

2.1. Porosity and Lack of Fusion

The other kinds of defects in lattices are generally not serious. It can take the form of internal voids within the struts or pore networks that form due to incomplete melting or poor consolidation. A 2024 study on polymeric strut-based lattices using X-ray computed tomography found that there were clear internal voids and geometry-related defects in the printed samples, and the morphology of these voids indicated that lack of fusion was a main reason [3]. Similar porosity in metal lattice structures can also be caused by low energy density, gas entrapment or an unstable melt pool [5-6].

There is a deficiency in the connection; therefore, struts are prone to buckling under load and joints may loosen. Once the void or unmelted area is in a crucial load path, a low-stress failure of the structure may occur. Lattice structures are already relatively slender and highly stressed due to struts, so even a small void can have a large impact on overall strength [4, 7].

2.2. Dimensional Deviation and Strut Waviness

Dimensional deviation is the difference between the desired and actual geometry of the printed lattice. Lattice members are relatively slender and are thus prone to over-design, under-design, waviness and cross-sectional distortion. Recently, a study was conducted to compare direct-print and assembled lattice structures, and it was found that inclined struts generate several disconnected contours during slicing, reduce interlayer contact, and thus have poor structural integrity [2].

Strut waviness and thickness variation are also visual defects. They alter the local stiffness, result in stress concentration, and thus increase the uncertainty of the mechanical analysis. In fact, even if the overall arrangement of the lattice is correct, there may be a large geometric deviation that affects the behaviour under compression and reduces the reproducibility of the samples [1, 3].

2.3. Surface Roughness and Contour Plurality

The second is a general problem of a rough surface in powder bed fusion and extrusion-based manufacturing. A high-roughness surface will reduce the fatigue life and influence the propagation path of surface cracks. Lattice structures have a relatively high roughness because thin struts have a large surface-to-volume ratio and are often printed in

orientations that expose them to staircase effects and partial melting [1, 5].

Contour plurality is the phenomenon of many small, disconnected contours in the cross-section rather than a single continuous load-bearing element. One of the main reasons reported for the lower performance of direct-printed lattices compared with assembled ones is that the contact area at the interface between layers is small, and thus bonding and structural continuity are inhibited [2]. Contour plurality is thus both a geometric and a process-related defect.

3. Related Problems

3.1. Mechanical Performance Loss

The first sign of production flaws is usually reduced mechanical properties. Defects reduce the maximum stress, specific energy absorption, stiffness and fatigue life. In the 2023 comparison of direct-print and assembled lattices, the assembled structures had better compressive strength and were less affected by manufacturing defects [2]. Therefore, the defect is not only superficial but can also change the structural logic of the lattice.

Numerical studies have also shown that defects can induce a high-stress concentration area. A finite-element model of a defected strut shows that shape and surface imperfections can alter the distribution of stress and strain under tension and compression [4]. Therefore, the results of the ideal-design simulation are likely too optimistic. If the above deficiencies are not rectified, the printed lattice will appear to have higher strength on paper than its actual performance.

3.2. Fatigue and Durability Issues

Defects also hasten fatigue failure. Repeatedly adding weight can cause the formation of small holes and weak spots in the connection over time. Lattice structures have concentrated stress cycles in the slender members and junctions, and this concentration can be severe. Recent review work on additive-manufactured lattice materials has shown that, although significant progress has been made in fatigue mechanism research and life prediction, many defects still negatively affect crack initiation and propagation [8].

Problems of durability are more severe for biomedical implants and light-weight aerospace components. A lattice may meet the first static-strength requirements but still fail prematurely under cyclic loading. Therefore, defect control should be implemented in the early stages of design rather than at the end of production [6-8].

3.3. Reliability and Qualification Problems

Production Defects will also cause qualification issues. It is not possible to certify a lattice design that has different print behaviours across different build jobs. It can also be seen that this will occur if the lattice does not meet the small performance window. Although recent studies in defect characterization have demonstrated the application of computed tomography and image processing for quantitative analysis of defects, it has also been found that it is difficult to maintain uniformity in such analyses for complex prints [3-4].

More broadly speaking, lattice structures are often based on idealised CAD models, and the actual manufactured parts have various defects. Therefore, it is not recommended to continue in the long run. Although a lattice may be theoretically optimal, if its defect distribution is too random, it will be rejected.

4. Causes of Defects

4.1. Process Parameters

Most of the faults stem from a bad process. Laser Power, Scan Speed, Layer Thickness, Nozzle Temperature and Build Orientation can all affect Porosity, Distortion and Bond Quality. Powder bed fusion is an energy-input method, so insufficient energy results in unmelted particles, and an excess of energy causes instability and dimensional error [3, 5]. Temperature fluctuations and unevenness in extrusion-based printing can lead to waviness and poor adhesion between layers [1].

4.2. Geometry and Orientation

Lattice geometry can also enhance defects. Slender struts, sharp joints and overhangs are all difficult to print precisely. The direction of the structure relative to the building direction should also be considered; otherwise, the inclined members will have broken contours and poor contact continuity [2]. As a result, some lattice types are inherently more prone to defects than others before considering process conditions.

4.3. Material and Powder Issues

The Other Cause of Difference is Material Quality. All of the above will change the shape and particle size distribution of the powder, moisture adsorption, resin stability. Irregular feedstock will have more voids, poor fusion and a rough surface. Therefore, the process monitoring and material characterisation of defects have been integrated more frequently [3, 6].

5. Inspection and Mitigation

5.1. Computed Tomography and Defect Mapping

X-ray computed tomography can be used to detect internal defects in the printed lattice to a certain extent. It can show hidden gaps, joints or thickness variations on the inside that are not visible from the outside. According to a CT-based study in 2024 on polymer lattices, defect distribution is unevenly distributed, and they are concentrated near strut junctions with more complex shapes [3]. CT can thus be used for inspection and to study the reasons for the appearance of defects.

5.2. Numerical Simulation

Numerical modelling can also show the location and type of damage in the field of stress concentration and fracture. Finite-element models can include surface roughness, shape deviations and voids to predict the structural behaviour more accurately [4, 7]. Simulation of an ideal lattice alone cannot be used to assess the actual risk of failure. The Model shows design defects that can improve the reality of the Design process and highlight areas for close control.

5.3. Machine Learning and Process Control

Recently, in a few review studies, it has been pointed out that machine learning is a very good way to get defect-free lattice structures. A general overview of the ML applications for property prediction, design optimisation, defect detection and real-time monitoring of additive manufacturing will be presented in 2025 [9]. The above instruments are particularly

suitable for lattice structures because the conventional method of trial and error cannot deal with a large number of interrelated factors efficiently. Therefore, machine learning will be used to predict and prevent the appearance of defects in advance.

6. Related Issues

Manufacturing Defects in lattices are also design and management problems. Decide whether to prioritise strength, weight reduction, manufacturability or inspection ease as the designer. Ignoring the feasibility of production will result in a theoretically ideal but unusable lattice. No Inspection will not find the concealed defects early. The best results are obtained by jointly designing the system of geometry, process and verification strategy [2, 3, 9].

Another problem is that the results of research are not being applied in industry. Although the laboratory experiments are in a perfect environment, machine drift and other problems with various operating environments of the production lines will also affect quality. For this reason, to manufacture defect-free lattices, high-quality materials and hardware need to be used, along with high-precision standards for calibration, monitoring and qualification. The literature has shown in recent years that the future of lattice printing will be a closed-loop, data-driven manufacturing ecosystem [8, 9].

7. Conclusion

The three-dimensional lattice structures produced by 3D printing generally have the following defects: porosity, poor fusion, dimensional error, uneven strut spacing, large surface roughness and warpage. These defects reduce strength, fatigue life and reliability; thus, the actual printed parts fall short of the ideal design goals [1-4]. The causes are distributed among process parameters, geometry and material properties; therefore, a single corrective measure is not feasible.

A combined-approach of design optimisation, computed tomography, finite-element modelling and machine learning-based monitoring is the best response. Improve the accuracy and stability of defect detection in the lattice structure to the extent that performance-enhancing lattice structures are also viable. With the development of additive manufacturing, the focus has gradually shifted from defect-aware printing to defect-controlled printing, and thus the application of lattice structures in high-performance applications is now safer and more reliable.

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