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A Comprehensive Review on Deformation Suppression in Additive Manufacturing Components

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ABSTRACT

From the 1980s to the present, the 3D printing technology, which has undergone decades of development, has gradually evolved from the early simple rapid prototyping technology to a variety of additive manufacturing technologies. Its application scope has expanded from the industrial sector to numerous other industries. Although 3D printing has many technological advantages compared with traditional manufacturing, it still has some problems, such as the deformation of components during the printing process. This paper discusses and introduces the possible deformation phenomena and their causes under different materials and printing methods, and focuses on the corresponding solutions for these deformations. These solutions include pre - planning and optimization during the printing process.

KEYWORDS

3D printing; Additive manufacturing; Metallic materials; Composite materials; Fused deposition modeling; Selective laser melting; Deformation

1 Introduction

3D printing, also known as additive manufacturing technology, is a special technique that builds three-dimensional objects by layering printing materials in a specific way based on 3D model files. As a new technology, the idea of 3D printing can be traced back to the layer-by-layer construction of ancient houses, while modern 3D printing technology originated in the United States in the mid-1980s. With the gradual maturation of 3D printing technology, it has further expanded into other related industrial fields such as aerospace, biomedicine, automotive and construction, and the components that can be manufactured by 3D printing have become more complex and precise. By the 21st century, 3D printing has become a rapidly developing and strongly growing emerging technology. A favorable piece of evidence is that from the 1980s to 2014, a period of 26 years, the 3D printing technology has grown by 27% in the global market, and its market value even reached 3.07 billion US dollars in 2014.

Based on the materials and technologies used, 3D printing can be roughly classified into the following categories: material extrusion, which includes fused deposition modeling (FDM, FFF, TPE); photopolymerization, which encompasses stereolithography (SLA) and digital light processing (DLP); material binder jetting; and powder bed fusion, which includes selective laser sintering (SLS) and electron beam melting (EBM). 3D printing has unique advantages in many aspects. For instance, it can directly print some parts with complex structures in one piece, reducing material waste in traditional production methods. Compared with traditional part manufacturing processes (such as casting or stamping), 3D printing requires a shorter production cycle and does not need specialized molds, significantly reducing production time.

However, in various 3D printing experiments and practical applications, printed components have a certain probability of experiencing deformation issues. These problems may be caused by different reasons but all affect the quality and usability of the finished products. This article will review the above-mentioned issues, presenting some possible deformation problems of 3D printed components. These problems will involve different materials and printing methods, and some representative examples will be introduced. This article will also focus on discussing and summarizing available solutions to the proposed problems and examples. These solutions cover different stages of the entire printing process, from pre-design and model prediction to printing equipment and process monitoring. The conclusion of the article will summarize the above parts and provide personal understanding on the importance and potential approaches for further in-depth research on 3D printing deformation.

2 Current challenges in additive manufacturing deformation for 3D printing

Currently, the mainstream 3D printing materials mainly consist of two types: metal materials and composite materials, and there are different printing methods for each. The following text will discuss the two types of materials and their corresponding printing methods respectively.

2.1 Deformation induced during the metal material printing process

As a widely utilized material, metallic materials occupy a pivotal position in global industries, rendering them a primary material in 3D printing applications. With the advancement of 3D printing technology, metal additive manufacturing (AM) has emerged, enabling the steel industry to produce metal components with complex geometries and high precision, which were previously unattainable through conventional manufacturing techniques due to significant technical and economic constraints. This technology encompasses various material feeding methods, among which Selective Laser Melting (SLM) has garnered the most attention and widespread adoption. SLM facilitates the production of metal components with intricate geometries in relatively shorter timeframes, while offering higher cooling rates. The ultrafine microstructures resulting from the non-equilibrium solidification process during printing enhance the performance of manufactured components. Consequently, SLM technology exhibits numerous advantages, including superior surface quality, minimal layer thickness, high density of formed parts, and excellent mechanical properties of structural components. A schematic diagram of the SLM process is illustrated in Figure 1.

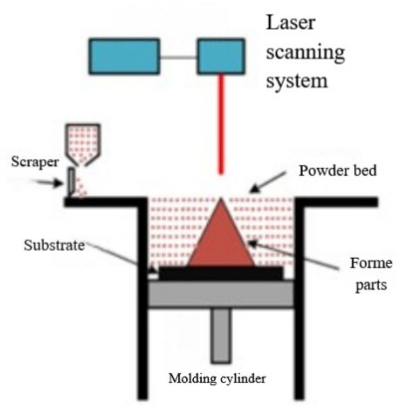

Figure 1 Schematic Diagram of Selective Laser Melting (SLM) Process

However, Yang Ruitao's research team discovered that components fabricated using Selective Laser Melting (SLM) technology exhibit certain degrees of deformation. As the high-energy laser beam irradiates and subsequently moves away from the substrate, the metal powder undergoes a rapid sequence of instantaneous melting followed by quick cooling and solidification. This process creates temperature gradients within the same deposition layer. Furthermore, the laser beam primarily heats the top layer of metal powder and its adjacent deposition layers, resulting in significant temperature gradients between different deposition layers. These temperature gradients, caused by uneven heating, lead to varying degrees of shrinkage in the materials of each deposition layer. Consequently, after the structural component is printed, substantial residual stresses accumulate internally. Residual stress constitutes one of the primary causes of structural deformation in fabricated components. Such deformation induced by additional stress can compromise dimensional accuracy, while severe residual stresses may cause noticeable warping or distortion of the component. This deformation can potentially lead to collisions between the component and the 3D printer's scraper (or roller), resulting in printing failures.

2.2 Deformation generated during the composite material printing process

Compared with metallic materials, composite materials emerged later, so their application in 3D printing is relatively less than that of metallic materials. Currently, the mainstream 3D printing of composite materials is mainly based on material extrusion (MEX), such as FFF and FDM. These processes generally use the machine's heated nozzle to deposit solid thermoplastic materials onto a substrate to manufacture parts. By using MEX technology, parts with high precision and complex shapes and structures can be manufactured without the use of special molds. At the same time, the application of composite materials can reduce various composite material wastes and promote sustainable environmental development.

In recent years, in order to improve the performance of additively manufactured parts, a large number of new composite materials have emerged. One advanced composite material is continuous carbon fiber reinforced thermoplastic composites (C-CFRTP). These materials generally use various high-performance thermoplastic polymers as their matrix and continuous carbon fibers as their reinforcement. Compared with the preparation of traditional composite components, due to the longer carbon fiber length, the components formed by this technology have better mechanical properties. Therefore, the printed components using C-CFRTP 3D have unique advantages such as good impact resistance, strong corrosion resistance, short molding time, and the ability for secondary processing, and have a broader prospect. The influence of carbon fiber length on components is shown in Figure 2.

The geometric features of C-CFRTP components are extremely complex, which poses a significant challenge to traditional manufacturing methods. Currently, 3D printing technology is mostly used for their production. After comparative experiments, it was found that the FDM (Fused Deposition Modeling) process is the mainstream method for manufacturing C-CFRTP components due to its lower cost, less material waste, and the ability to quickly change the thermoplastic materials used. In the FDM process, thermoplastic raw materials are heated to a molten state through the machine's nozzle and extruded. Under the control of a computer, they are laid down on the printing platform along a

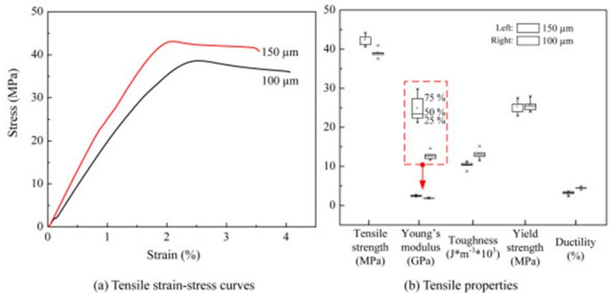

Figure 2 Impact of carbon fiber length (carbon fiber content: 5 wt%)

preset path. After rapid cooling and solidification, they bond together to complete one layer. The platform then moves down, and the next layer is printed until the entire component is completed.

However, the team led by Zhou Jianming discovered during the printing process that there was a deformation problem when using the FDM technology to print C-CFRTP components. To investigate the cause of this deformation, they conducted experimental tests using a self-built C-CFRTP pre-impregnated 3D printer and measured the warpage deformation of the components. During the tests, the team found that due to the significant differences in parameters such as thermal conductivity and coefficient of thermal expansion between the carbon fibers and thermoplastic resin materials used, a large temperature gradient would occur within the component during the printing process. This would result in unequal thermal stresses in the deposited component, causing different degrees of deformation at various parts of the component and leading to warpage. This warpage would seriously affect the assembly and use of the printed components.

3 Current resolution methodologies

The preceding section has provided a comprehensive overview of the deformation issues encountered during the printing process when utilizing various materials. The subsequent discussion will delve into the 3D printing methodologies employing these distinct materials, addressing the aforementioned challenges and exploring corresponding solutions.

3.1 Optimization strategies for Selective Laser Melting (SLM) process in metallic materials

3.1.1 Thermal deformation optimization of SLM printed structural components based on process parameter regulation

For the SLM process, printed parts typically undergo several alternating rapid heating and cooling cycles, making the generation of stress inevitable and leading to deformation of the printed parts. If the printing parameters are modified and adjusted in the early design stage before printing begins to reduce the residual stress produced, the deformation of the parts can be reduced from the design perspective. However, using traditional methods to explore the combination of printing parameters requires a relatively long time. The current mainstream approach is to use conventional finite element simulation methods, which can significantly reduce the time spent but usually at a high computational cost.

In response to the above situation, Chen Kemin established a rapid prediction method for the deformation of SLM printed parts, using a quasi-static thermo-mechanical model and a thermal circuit network model to predict the temperature field changes and variations during the SLM printing process. He adopted the quasi-static thermo-mechanical model (Quasi-static Thermo-mechanical Model, QTM), which can calculate the thermal deformation of the part in real time during the printing process. Meanwhile, for the rapid prediction of component deformation, the thermal circuit network model (Thermal Circuit Network, TCN) developed by Chen Kemin can quickly predict the temperature field changes of the part under different printing process parameter combinations.

In summary, Chen Keming successfully developed a sophisticated multi-physics model by constructing the aforementioned two models, utilizing a novel finite element simulation approach. This composite model effectively simulates the intricate thermo-mechanical coupling behaviors during the layer-by-layer manufacturing process of Selective Laser Melting (SLM). Research findings indicate that the established model can accurately predict the temperature field evolution and overall deformation of components during the SLM printing process. The predictive results demonstrate consistency with those obtained from traditional finite element methods, while significantly outperforming conventional approaches in terms of computational time and cost efficiency.

3.1.2 Residual deformation optimization in the SLM printing process based on multi-objective structural topology

In addressing the reduction of deformation through preliminary design approaches, Yang Ruitao's team opted to employ topology optimization to mitigate residual deformation during the SLM (Selective Laser Melting) printing process.

Topology optimization, as an advanced design methodology, offers a highly flexible design space, enabling the creation of high-performance, lightweight, and multifunctional structural designs. However, the components derived from this method often exhibit complex geometric structures that are challenging to fabricate using traditional manufacturing techniques. SLM technology, on the other hand, is particularly well-suited for constructing such models. Yang Ruitao integrated topology optimization design methods with metal 3D printing technology, leveraging the strengths of both to propose a multi-condition, multi-objective optimization approach aimed at minimizing residual deformation and structural average compliance in metal 3D printing. Additionally, he incorporated "manufacturing constraints" related to residual deformation during the structural design phase. This methodology effectively reduces residual deformation in metal 3D printing while ensuring structural performance, with the efficacy of the optimization algorithm validated through case studies. Figure 3 presents the specific multi-objective optimization model equations.

$$
\begin{aligned}
\text{min}: \;& f = (1-\omega) f_c + \omega f_u \\
\text{s.t.}: \;& \boldsymbol{KU} = \boldsymbol{F} \\
& \boldsymbol{K}^{(m)}\boldsymbol{U}^{(m)} = \boldsymbol{F}_{inh}^{(m)} \\
& V_f = \frac{\sum_{e=1}^{N} x_e V_e}{\sum_{e=1}^{N} V_e} \le V_f^* \\
& \begin{cases} x_e = 1 & \text{when } x_e \in \Omega_1 \\ x_e = x_{\min} & \text{when } x_e \in \Omega_0 \;;\; e = 1, 2, \ldots, N \\ x_{\min} < x_e < 1 & \text{when } x_e \in \partial\Omega \end{cases}
\end{aligned}
$$

Figure 3 The multi-objective optimization model involved

To further validate the efficacy and applicability of the algorithm, Yang Ruitao conducted a study utilizing a three-dimensional corner support structure. The research findings indicate that in the multi-objective optimization design considering residual deformation in metal 3D printing, the maximum residual deformation of various three-dimensional corner support structures exhibited a significant reduction, which aligns with the theoretical conclusions derived from the aforementioned algorithmic model. This outcome reaffirms the validity and applicability of the multi-condition multi-objective optimization algorithm developed by his team.

3.1.3 Optimization of deformation in metal printed components via intelligent guided laser irradiation

A prevalent issue in the Selective Laser Melting (SLM) process is the accumulation of heat generated by laser irradiation within the printed components, leading to deformation, defects, and residual stresses, particularly in parts with extremely thin features. To address this challenge, researchers at the University of Michigan developed a novel software named SmartScan in 2022. This innovative technology optimizes the laser printing path through intelligent laser guidance, considering the heat flow patterns within the given component and analyzing the thermal properties of the component's geometry and material. It then maps an optimized scanning sequence to minimize heat accumulation in critical areas, thereby enhancing 3D printing by reducing detrimental heat build-up in laser powder bed fusion printers. This advancement enables the 3D printer to fabricate complex metal and plastic components at accelerated speeds.

To evaluate its efficacy, the research team employed laser imprinting to create identical patterns on two stainless steel plates. The first plate was processed using the SmartScan technique, while the second plate was subjected to conventional printing patterns. Comparative analysis revealed that the SmartScan-processed plates consistently exhibited less warping and demonstrated more uniform heat distribution during the marking process when compared to alternative printing methodologies. Figure 4 presents a comparative analysis of the experimental results from two distinct trials.

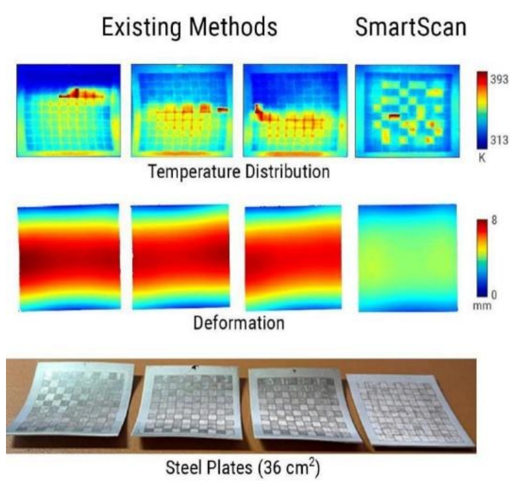

Figure 4 Comparative analysis of temperature profiles in two experimental trials

3.2 Optimization strategy for C-CFRTP (composite materials) enhancement

3.2.1 Optimization of deformation in C-CFRTP components based on temperature adjustment

The research conducted by Jianming Zhou's team revealed that during the 3D printing process of C-CFRTP components, temperature-related parameters, such as the build plate temperature and nozzle temperature, significantly influence the temperature field of C-CFRTP components, thereby altering the temperature gradient. This has a substantial impact on the warpage deformation values of the formed components [12]. To mitigate the effect of temperature on component deformation, they employed a self-developed C-CFRTP pre-impregnated 3D printer and established an experimental platform comprising thermocouples and an infrared thermal imager to monitor the temperature field variations during the 3D printing of C-CFRTP.

Through systematic investigation of the bed temperature and nozzle temperature of the 3D printing apparatus using this experimental setup, the research team identified an effective method to mitigate deformation in C-CFRTP components. The team conducted 3D printing of C-CFRTP components under varying bed temperatures, with each temperature replicated three times. The components were subsequently measured along the Y-axis using the Mitaka PF-60 instrument to quantify warpage deformation, followed by comprehensive analysis of the experimental results. As illustrated in Figure 2.5, the measurement data demonstrate a progressive reduction in warpage deformation of 3D-printed components with increasing bed temperature, with the most significant reduction in deformation observed at a bed temperature of 65°C. To further investigate this phenomenon, the team employed infrared thermography to measure isothermal contours within the XY plane and Z-axis of the printed components. The results conclusively demonstrate that as the 3D printing bed temperature increases, the thermal gradient experienced by C-CFRTP progressively decreases, leading to reduced thermal stress and consequently diminished warpage deformation in the fabricated components. Figure 5 presents the variation of the warpage deformation values of C-CFRTP components with the baseplate temperature during the experiment.

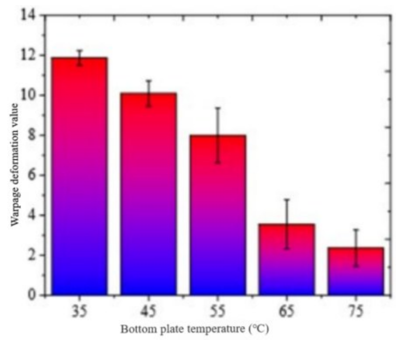

Figure 5 Variation of the warpage deformation value of C-CFRTP components with the baseplate temperature

3.2.2 Optimization of the deformation of printed composite structures based on printing speed

During the 3D printing and forming process, composite material components experience curing deformation at room temperature due to the thermal expansion and contraction effects of the materials, the curing shrinkage effect of the matrix resin, and the differences in thermal expansion coefficients between the components and the mold materials. In response to this situation, Master Yu Lintao from Chongqing University led his team to optimize this problem from multiple aspects. In the preliminary research, they found that the change in the nozzle speed of the printing machine would affect the curing deformation of the final part. Further research revealed that the moving speed of the printing nozzle directly influences the forming time and quality of the formed part. The faster the printing speed, the quicker the forming speed of the formed part. However, an excessively high printing speed may also lead to incomplete filling of the formed part and phenomena such as stringing. To optimize the curing deformation problem, Master Yu Lintao established numerical models of curing deformation at different printing speeds respectively. By comparing the distribution of curing deformation at different printing speeds, the influence trend of the printing speed on curing deformation was studied.

Through model establishment and experimental research, Master Yu Lintao discovered that, when other factors remain constant, the maximum curing deformation of the composite stiffened panel structure decreases as the printing speed increases during the continuous increase of the printing speed. Figure 6 shows the influence of different printing speeds on the curing deformation of the stiffened panel structure.

Further research has revealed that during the 3D printing process, an increase in the printing speed significantly shortens the forming time of the molded part, resulting in a reduction in the cooling time of the completed portion. At this time, heat is transferred to the surrounding completed units and the environment, leading to continuous cooling. As the nozzle moves along the printing path, the component undergoes repeated cycles of temperature decrease and increase. A higher printing speed shortens the duration of temperature changes, thereby generating smaller thermal

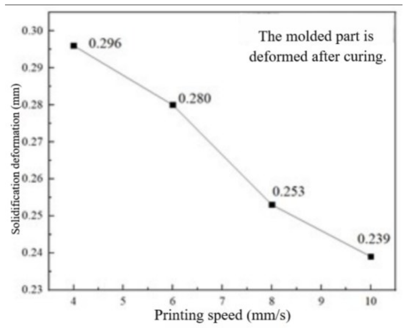

Figure 6 Diagram shows the variation of the maximum curing deformation of the stiffened panel structure under different printing speeds.

stresses and reducing the curing shrinkage deformation. This fully demonstrates that the curing shrinkage deformation of the molded part can be reduced by increasing the printing speed within a certain range.

4 Conclusion

This paper summarizes several factors currently influencing the deformation of additive manufacturing components, including thermal stresses induced by temperature gradients due to material variations and residual stresses caused by instantaneous temperature changes during laser irradiation. Addressing the deformation issues in additive manufacturing components, this study explores various materials and printing methods, synthesizing potential solutions from diverse sources. The data referenced in this paper is limited to publications from the past decade, presenting a temporal constraint. While the paper discusses deformation issues and potential solutions for both composite and metallic materials, it only summarizes a subset of printing methods, revealing significant limitations and gaps. Further exploration of additional printing techniques and research contexts is warranted. During the preparation of this manuscript, the author observed an imbalance in the current research landscape concerning deformation in 3D printing. The majority of discussions focus on the phenomenon of deformation itself, often reiterating established notions, while only a limited number of articles address optimization strategies for various deformation issues. It is hoped that future research will expand on this critical aspect.

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