In-process Temperature Monitoring during Fused Filament Fabrication

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Fused filament fabrication (FFF), an additive manufacturing technique, unlocks alternative possibilities for the production of complex geometries. In this process, the layer-by-layer deposition mechanism and several heat sources make it a thermally driven process. As heat transfer plays a particular role and determines the temperature history of the merging filaments, the in-process monitoring of the temperature profile guarantees the optimization purposes and thus the improvement of interlayer adhesion.

Keywords: In-process monitoring ; FFF ; Inter-layer adhesion ; Heat transfer

1. Introduction

Additive manufacturing (AM) is a process of joining, layer-by-layer, a 3D object from 3D models developed in the 80s of the 20th century [1]. Due to the significant advances in the development of this process, such as the reduction in time/cost and the possibility of creating complex geometries, it has attracted a lot of attention in the last decades through different applications (e.g., aerospace, automotive, biomedical, etc.) [2][3]. These characteristics, incorporated with AM technologies to fabricate complex geometries in the micrometer order, have made this technology an advanced industry [4].

One of the most important features in FFF is that the bonding location is the point of failure. During the material deposition, a hot layer is deposited on/beside the previous layer(s) that are already under the cooling stage. This issue causes the cooling and re-heating of filaments, resulting in a small-time gap where the polymer–polymer interfaces are above the glass transition temperature (Tg for amorphous materials) or crystallization temperature (Tc for semi-crystalline materials) . On the other hand, the adhesion of layers for the FFF parts is thermally driven. Their temperature history should be considered as a critical variable in characterizing the mechanical characteristics of the final parts [5][6].

Although (FFF)-3D printing has attracted significant attention in recent years, several review papers on the 3D printing of polymeric (or even composite) materials have focused on critical characteristics and challenges, such as the mechanical properties of fabricated parts, application of various materials, and the process design. Based on the existence of review papers that consider the different aspects of the FFF, such as heat transfer, further review on the in-process monitoring of the temperature profile during FFF is still missing. This paper contributes to persuading readers of its noteworthy aspect of heat transfer and its remarkable impact on the bonding/strength of 3D-printed parts. Research studies that consider the heat transfer are discussed both experimentally and numerically. In addition, a comparison representing the advantages and limitations of each approach is also singled out.

2. FFF Parameters and Their Impact on Part Quality

The mechanical behavior of FFF parts is usually lower than the parts fabricated by traditional manufacturing processes. Although the main drawback is due to the principle involved in the production stage, the wrong choice of the process parameters was found to be more essential. As the role of FFF parameters determines the build cost and time, developers and designers must understand the influence of process parameters to improve the quality of the final components [7][8][9].

As an important indicator, they proposed to take into account the mechanical performance of the fabricated parts during the AM/RP manufacturing process. More precisely, in FFF machines, the process parameters have a considerable impact on the mechanical performance of the final part during the manufacturing process. An unsuitable choice of the process parameters could be the main reason for their poor mechanical characteristics. Controlling and optimizing the process parameters on the part quality, which is the strength of the FFF parts, could be improved, and, thus, it is essential to understand their importance [10].

As discussed, the quality of a final object fabricated by the FFF process mainly relies on applied parameters. The main issues and areas of concern of any FFF user concerning the quality are the build time and build cost. There are much lower mechanical properties of parts fabricated by FFF, compared to traditional manufacturing processes, where several parameters affect the final parts. It is important to consider the main parameters and their impact on the final part in order to improve the part quality.

3. Role of Heat Transfer in FFF

In the FFF process, a thermoplastic polymer is fed into a liquefier that extrudes a filament while moving in successive X-Y planes along the Z direction to fabricate a 3D part in a layer-by-layer process. Consequently, as the deposition progresses, the hot filament is deposited onto the previously deposited filaments, and are consequently in the process of cooling. This causes their re-heating, defining a time when the interfaces of contacting filaments are above the glass transition temperature (Tg) in the case of amorphous materials or the crystallization temperature (Tc) for semi-crystalline materials, which is necessary for proper bonding to take place. Therefore, each filament should be sufficiently hot during deposition, but not too hot, to avert deformation due to the gravity and the weight of the filaments deposited in subsequent layers. There are several heat transfer mechanisms during FFF: (1) Heat induced by the liquefier; (2) Convective cooling of the filaments with the air: the effect of heat transfer coefficient (hconv) is inevitable; (3) Heat exchanges between the adjacent filaments: the conductance and deposition sequences control the interaction intensity; (4) Heat brought by the support plate: this is defined as the conduction controlled by the thermal contact conductance and contact area; (5) Radiative losses: This consists of radiation between the filament and surroundings and radiation between adjacent filaments; (6) Heat source from the exothermal crystallization for semi-crystalline polymers [11].

Accordingly, the following parameters impact the part quality and mechanical strength of the final parts: the liquefier temperature, platform temperature, ambient temperature, print speed, layer thickness, and part orientation. The interaction of the mentioned parameters plays a vital role in determining the mechanical properties of the printed parts. In what follows, a brief explanation of the influence of the mentioned parameters on the mechanical behavior of the printed parts has been taken into consideration.

Regardless of the study on the influence of parameters on neck-growth or the neck-growth prediction by viscoelastic models, there is still a lack of practical knowledge toward the consideration of the temperature-dependent viscosity and its influence on the coalescence of two adjacent filaments. To eliminate the mentioned missing spot, a thermo-mechanical approach is an essential manner by applying the results of the temperature evolution of filaments at their interface.

4. Temperature Evolution of Filaments in FFF

They finally concluded that the temperature of the top layer just before the deposition of a new layer could be considered as an indicator for the degree of warping and cracking.

The in-process monitoring of the temperature profile should be sufficiently precise and quick in order to track the filament cooling and re-heating peaks arising from the contact between freshly and previously deposited filaments. A thorough investigation of the in-process monitoring of the temperature profile during FFF has been realized in this section.

4.1. In-Process Monitoring of Temperature Profile

The objective of undertaken work is to investigate in-process monitoring of temperature profiles during deposition. In almost all the presented works by researchers, combined experimental and numerical simulations were carried out to realize the temperature evolution of filaments better. Up to now, many techniques have been developed to investigate and characterize the temperature evolution during FFF. In order to further understand the characteristics of the recorded temperature profiles, we have divided them into two separate classifications: global temperature recording on the external surface of deposited layers and local temperature recording at the interfaces of adjacent layers. In addition, efforts have been taken into account to include experimental/numerical and experimental works in both classifications.

4.2. Advantages and limitations of in-process monitoring approaches

Local and global in-process temperature monitoring has their advantages and limitations. An IR camera has a limited scan quality in complex geometries, while thermocouples could be fixed to a limited number of points of a geometry [83, 127]. With reference to the variety of researches in real-time monitoring, particular attention has been paid by Vanaei et al. [12] to carry out a thorough experimental comparison of the mentioned techniques. The obtained results from both approaches with the same conditions, same fixed points of measurement, and simultaneously illustrate the importance of the proposed roadmap. The temperature peaks that the IR camera has recorded were highly overestimated in comparison with the recorded data by K-type thermocouples. For this reason, the interval of peaks between the two approaches, plotted as contours for corresponding layers, affirm the nature of each measurement technique.

5. Summary and conclusions

FFF unlocks alternative possibilities for the production of complex geometries. In this process, the layer-by-layer deposition mechanism and several heat sources make it a thermally driven process. As heat transfer plays a particular role and determines the temperature history of the merging filaments, in-process monitoring of temperature profile guarantees the optimization purposes and thus the part quality improvement.

This review paper summarized the most attractive research on the in-process monitoring of temperature profiles. Detective devices play an essential role through the prosperity of in-process monitoring of temperature profiles. IR cameras and thermocouples are the most common techniques for this purpose and have attracted much attention from researchers. Furthermore, model-based approaches have also taken a significant role in this regard. We placed special emphasis on highlighting the local and global in-process monitoring techniques to carry out their findings and have an overall comparison through them.

With reference to both experimental and numerical efforts, significant progress has resulted from in-process monitoring of temperature profiles. However, it was found that a precise approach is still required to be developed for monitoring of temperature profile and consequently for optimization purposes.

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