Data-driven framework towards an AI-assisted multiparametric qualification for FFF-processed components

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Additive manufacturing (AM) has experienced an exponential growth in recent years, evolving from a simple rapid prototyping tool to a key technology for the production of complex structural components [1]. As a result, ensuring the reliability, repeatability, and certification of additively manufactured parts has become a critical challenge, particularly when dealing with advanced geometries that cannot be produced using conventional manufacturing techniques. Among these, auxetic structures represent a relevant example, as their geometric complexity makes AM the only viable fabrication route. In addition to their unique deformation mechanisms, these structures are particularly attractive for engineering applications requiring enhanced energy absorption and vibration damping capabilities [2,3]. However, additively manufactured components, particularly those with complex geometries intended for structural applications, such as auxetic structures, require extensive procedures to ensure their reliability, reproducibility, and long-term performance under service conditions heading toward formal qualification and certification [4,5]. In this context, the development of standardized approaches supported by structured material datasets is a necessary step towards data-driven and AI-assisted certification frameworks.

This work addresses these challenges through a systematic physico-chemical and thermal characterization of two engineering polymers widely used in fused filament fabrication (FFF): polyether ether ketone (PEEK) and thermoplastic polyurethane (TPU), selected due to their extensive use in engineering applications and their ability to cover a broad range of mechanical behaviors, from high stiffness and thermal resistance to flexible and elastomeric responses. Due to the strong dependence of their properties on thermal history and processing conditions, a comparative analysis of raw filament and printed parts was performed. Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) were selected in this initial series of tests to evaluate chemical modifications, thermal stability, degradation behavior, and thermal transitions associated with the FFF process. Filaments were processed under different temperature conditions in order to intentionally induce varying levels of material degradation, generating a controlled dataset that serves as a reference baseline for comparison with components potentially degraded during AM processing.

Based on selected indicators derived from FTIR, TGA, and DSC, a Python-based multi-parameter workflow was developed to define acceptance criteria and process control windows, enabling the classification of printed components as suitable or non-suitable for their intended application (Figure 1). This computational approach supports the automated identification of process-induced deviations while facilitating the generation of a structured and scalable material database.

In the long term, this framework opens the door to the implementation of AI-assisted certification methodologies, where machine learning models can be trained to predict material integrity and component suitability directly from characterization inputs. Such approaches would allow rapid, automated assessment of additively manufactured parts, reducing experimental burden while increasing reliability and consistency in industrial qualification processes. Furthermore, the extensibility of the proposed workflow to additional materials and processing conditions supports the creation of comprehensive material libraries, contributing to the development of interoperable and intelligent certification systems for additively manufactured polymer components.

References

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Figures

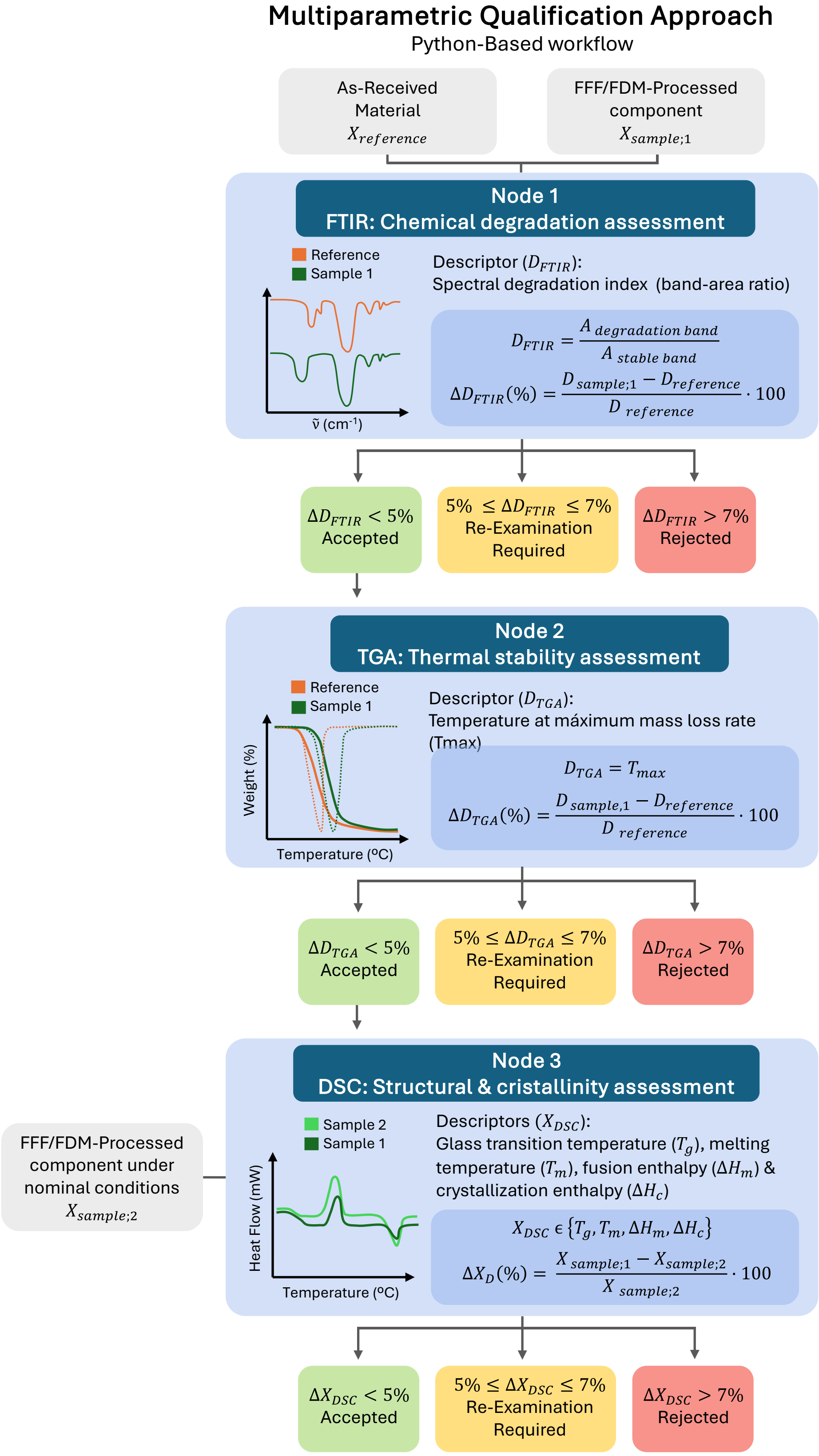

Figure 1. Graph-based representation of a multiparametric approach for the qualification of additively manufactured components, implemented via a Python-based workflow. Each node encodes quantitative descriptors extracted from experimental datasets. The first two nodes correspond to the assessment of the filament and the additively manufactured component, respectively, through a differential analysis with respect to the reference material (commercial filament). This strategy enables the concurrent evaluation of multiple thermo-chemical features within a unified analytical framework. The third node is not intended to quantify degradation, but rather to resolve deviations in the thermophysical properties of the processed material relative to material produced under nominal processing conditions, thereby supporting an integrated interpretation of material performance. The acceptance criteria illustrated in the figure are intentionally conservative; however, within the workflow they are fully programmable and can be adapted according to user-defined requirements.