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Common Imperfections and Mechanical Performance of Additively Manufactured Scaffolds

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Abstract

Direct Ink Writing (DIW) manufacturing technique enables the fabrication of metal-ceramic composite structures. This study examined core-shell filaments composed of 316L stainless steel and Al_2O_3 ceramic, produced through co-axial DIW followed by reactive sintering within the MULTIFUN3D project. Scaffolds made of pure ceramic filaments are also considered. Fabrication-induced imperfections, including porosity, non-circular cross-sections, and filament penetration are observed. Their influence on structural performance is evaluated by interpreting the experimental results obtained from mechanical tests with the aid of corresponding numerical simulations. The final goal is to identify the most effective improvements to be introduced into the manufacturing process to ensure consistency between design and actual production performance.

Keywords: *Metal-ceramic composites; additive manufacturing; mechanical performance; imperfections.*

1. Introduction

Additive manufacturing (AM) has emerged as a fabrication technology capable of producing complex geometries and customized structures (Bandyopadhyay et al., 2019). Direct Ink Writing (DIW) is an AM technique based on extrusion of pre-mixed inks and powders followed by sintering at elevated temperatures. DIW has been used to

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fabricate metal-ceramic core-shell architectures with controlled geometries (Biasetto et al., 2021; Biasetto et al., 2024). In practice, however, the final printed components often deviate from their nominal design due to process-induced imperfections (Sohrabian et al., 2021, Entezari et al., 2020). Typical defects include variations in core diameter, geometrical distortions, and filament misalignment in the scaffold architecture. These factors affect both load-bearing capacity and structural stability, and can lead to significant deviations in mechanical performance compared to predictions. This work focuses on the mechanical behavior of 316L-Al_2O_3 scaffolds produced by AM. The results obtained from compression tests on actual components are interpreted with the aid of numerical simulations, which highlight the effects of imperfections.

2. Experimental Program

Pure ceramic and metal-ceramic cylindrical filaments made of Al_2O_3 with a 316L stainless steel core were printed by coaxial DIW and sintered at 1350°C as part of a cooperative research project called MULTIFUN3D. The overall dimensions were approximately 40 mm in length and 1.4 mm in total diameter. All filaments were mechanically characterized through four-point bending tests conducted under displacement control at a loading rate of 0.5 mm/min (Farrokhtar et al., 2025).

In addition, scaffold samples were also produced and subjected to uniaxial compression tests. The scaffolds had a prismatic geometry with approximate dimensions 20 mm×20 mm×10 mm. Observations revealed several fabrication-induced imperfections, including deviations from the nominal circular shape of the cross sections of the individual filaments, misalignments with respect to the ordered design geometry, and partial penetration between adjacent layers. This information was included in numerical analyses performed to quantify the influence of these factors on the load-bearing capacity of the produced components.

3. Numerical Simulations

Numerical modeling requires the precise definition of the geometrical configuration, loading conditions, and material properties of the investigated element.

Fig. 1 represents the designed three-dimensional arrangement of filaments in the scaffolds.

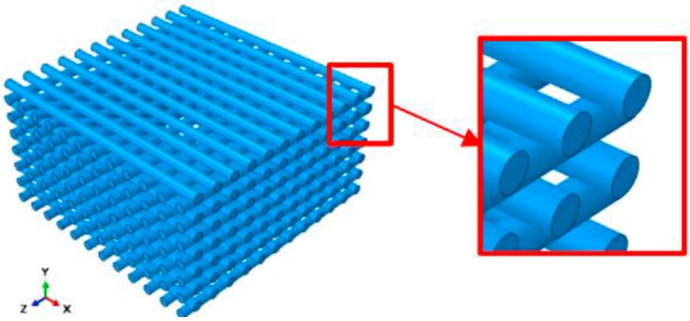

Fig. 1. Schematic of 3D scaffold simulation.

Alternative geometries resulting from the manufacturing process were also considered, see Fig. 2. In particular, the elliptical cross-sections sketched in Fig. 2(b) preserve the design areas while exhibiting an overall height consistent with the measured dimensions of the fabricated scaffolds, which is reduced compared to its theoretical value.

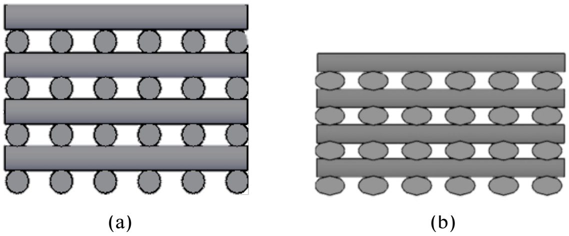

Fig. 2. Alternative geometric configurations: (a) Ideal geometry; (b) Elliptical cross sections.

The constitutive law adopted for the ceramic material in the preliminary analyses presented here is linear elastic. All simulations were performed using the commercial software Abaqus (Dassault Systèmes, 2023).

The force-displacement curves represented in Fig. 3 are obtained from the 3D simulation of the compression test on the two scaffold models schematized in Fig. 2. The strong influence of alternative assumptions is highlighted by the significantly different values resulting for effective stiffness and peak load, which here corresponds to the onset of geometrical instability.

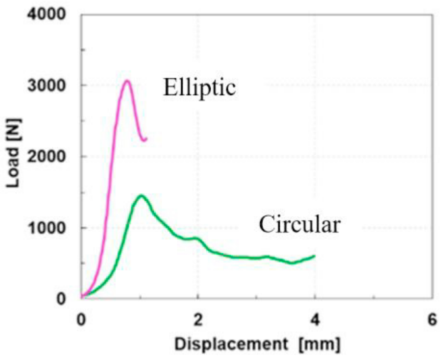

Fig. 3. Simulation results of the compression test obtained by assuming circular or elliptic cross section with equivalent area.

4. Conclusion

The present study aimed to understand and quantify the role of common imperfections on the mechanical response of elements produced with DIW additive technology. The results demonstrate that deviations from ideal geometries due to manufacturing play a key role in determining actual characteristics.

This insight underlines the importance of advanced process control and defect minimization strategies to ensure consistency between design intent and real performance, thereby improving the reliability and applicability of components for structural and biomedical applications.

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