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A critical review of the article

Una revisión crítica del artículo

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Currently, 3D printing has become an increasingly popular technology across various industries, including automotive, aerospace, defense, and sports, to produce functional parts with complex shapes. The use of composite materials in 3D printing has shown better performance in terms of mechanical properties than conventional filaments, enabling these components to withstand rigorous usage conditions, such as impact testing.

A recent study conducted by Chihi *et al.* (2023) examines the impact behavior of 3D printed carbon fiber (CF) reinforced Polyethylene Terephthalate Glycol (PETG) composite using the Split Hopkinson Pressure Bar (SHPB) test. The researchers employed Fused Filament Fabrication (FFF) as a printing technique to produce the test specimens. The objective was to assess the influence of two infill patterns (rectilinear and honeycomb) and three infill densities (20%, 50%, and 75%) in 13 mm cubic samples on the material's dynamic properties. Four impact pressures (1.4, 1.7, 2, and 2.4 bar) were applied to characterize the material at different strain rates. When describing the behavior of a sample, we refer to infill density in terms of percentage and use the abbreviations REC and HON for rectilinear and honeycomb infill patterns, respectively.

The SHPB apparatus consists of a striker that impacts two aligned bars (incident and transmitted), between which the sample is placed. Strain gauges on the bars record the incident, reflected, and transmitted pulses, which are essential for obtaining the stress-strain (σ-ε) and strain rate-strain ($\dot{\varepsilon}$-ε) curves. The reflected and transmitted pulses are directly proportional to the strain rate and the stress applied to the sample.

According to the authors, the experimental results demonstrate the accuracy and reliability of the method for evaluating the behavior of CF-PETG at high strain rates. A significant influence of the wave amplitudes due to the striker's impact velocity was observed. Additionally, a high-speed camera was used to monitor the evolution of deformation and the kinetics of damage in the samples.

The combinations where the samples suffered macro-damage or permanent failure were 20%-REC and 20%-HON for all pressures, 50%-REC, 50%-HON, and 75%-REC at pressures of 2 and 2.4 bar. The rest of the tests exhibited micro-cracks and an elastic-plastic behavior. It was observed that a higher infill density improves mechanical properties. The honeycomb pattern showed better performance in resistance to macro-damage and permanent failures compared to the rectilinear pattern due to a better stress distribution.

The recorded (σ-ε) curves show that increasing the strain rate makes the linear region more prominent and gradually increases the yield stress, indicating greater rigidity and energy consumption of the sample. When comparing the (σ-ε) curves of the infill patterns, the honeycomb pattern exhibits higher elastic moduli, more pronounced linear plastic regions, and maximum stresses almost twice as high compared to the rectilinear pattern, which showed more evident regions of plastic instability.

Both infill patterns improve compression strength (CS) and increase the compression modulus (CM) as the infill density increases. In tests at 1.7 bar, the honeycomb pattern recorded compression stresses of 17.94 MPa, 44.89 MPa, and 55.07 MPa for densities of 20%, 50%, and 75%, respectively. The rectilinear pattern showed strengths of 13.04 MPa, 21.68 MPa, and 35.85 MPa for the same densities. A maximum increase of 46% in stiffness was observed for the honeycomb pattern and 24.5% for the rectilinear pattern between the samples of lowest and highest density at a pressure of 1.7 bar. This trend is due to the increase in density reinforcing the bonding

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between layers, resulting in greater stiffness and lower deformation capacity.

To define the strain rate sensitivity as a function of CS and CM of CF-PETG, second-order polynomial mathematical models were established for the samples 75%-REC, 50%-HON, and 75%-HON, which did not present dynamic failure, where the coefficients of determination ranged between 0.93 and 0.98. The models showed that the maximum stress in samples 50%-HON and 75%-HON increases proportionally with the strain rate, while in sample 75%-REC, a threshold in maximum stress was presented at a strain rate of 587 s^{-1}. The compression modulus increased convexly in samples 50%-HON and 75%-HON and proportionally in sample 75%-REC.

The high-speed images corroborated the results of the final state of the samples. Macro damage and final fracture were detected in samples with 20% density at pressures of 1.4 and 1.7 bar for both patterns. Macro damage was also observed in samples 50%-REC, 50%-HON, and 75%-REC at a pressure of 2 bar. The sample 75%-HON did not show macro-damage at any pressure.

The behavior of stress and strain rate over time was described in five regions for samples without macro-damage and six for those that did present them. The highlight of these graphs is that they exhibit a second peak in the strain rate, associated with the onset of macro-damage, confirming the failure of the sample. In samples without macro-damage, the strain rate takes negative values due to the elastic recovery of the sample.

The following highlights aspects that were unclear during the experiments to obtain the dynamic properties of CF-PETG. Chihi *et al.* (2023) mention that the bars used are high-strength martensitic steel and 20 mm in diameter. However, to reproduce the experiments, it would be desirable to detail the mechanical properties and geometric characteristics of the components of the SHPB machine, as these aspects influence wave propagation and the accuracy of the results (Chen & Song, 2011; Govender *et al.*, 2018; Kariem *et al.*, 2018, 2019; Miyambo *et al.*, 2023). Likewise, it would be helpful to know the impact velocity of the striker. Previous studies use aged martensitic steel bars and show that high-frequency oscillations in the incident pulse are eliminated using a pulse shaper (Chen *et al.*, 2003; Parry *et al.*, 1995; Samal & Sharma, 2021). The use of a pulse shaper in the research is evident, but information about its material and geometric parameters is lacking. To obtain a constant strain rate, it is necessary to modify the shape of the incident pulse, as it directly impacts the reflected pulse, which is a function of the strain rate (Parry *et al.*, 1995; Vecchio & Jiang, 2007). Upon analyzing the results, only one other study was found on CF-PETG at high strain rates (Daly *et al.*, 2024), conducted by the same authors and using the same results for the honeycomb pattern. However, some studies characterize the mechanical properties of CF-PETG under quasi-static loads, showing compression strengths between 11.52 MPa and 60 MPa, depending on the printing parameters (Batista *et al.*, 2023; Daly *et al.*, 2024; Faidallah *et al.*, 2024; Jain *et al.*, 2023; Mansour *et al.*, 2018; Patil *et al.*, 2024; Patil & Sathish, 2024). It is noteworthy that the reported maximum dynamic compression stress is similar to that obtained in quasi-static tests when a higher value under dynamic loads would be expected, as occurs in other studies (Ji *et al.*, 2024; Lei *et al.*, 2020; Priyanka *et al.*, 2021; Utzeri *et al.*, 2021).

One of the essential requirements to validate the results of SHPB tests is dynamic equilibrium, which involves evaluating the relationship between the loads applied on the faces of the specimen. This ratio should be equal to or less than 0.05 (Song & Chen, 2005; Vecchio & Jiang, 2007; Xu *et al.*, 2018). In this work, this equilibrium is not demonstrated. Additionally, to reduce the self-alignment time of the specimen and the bars, it is necessary to use lubricant between them, reducing friction and improving coupling for wave transmission (Aghayan *et al.*, 2022; Chen & Song, 2011; Gama *et al.*, 2004).

The mismatch of mechanical impedance between the bars and the sample causes when the compression wave reaches the interface between the bar and the sample, part of the wave is reflected as a tensile wave, and another part is transferred to the sample and subsequently to the transmitted bar (Gama *et al.*, 2004). When the impedance of the bars is much greater than that of the sample, the reflected wave almost equals the incident wave in magnitude, and the transmitted wave has a very small amplitude, which can be confused with electrical noise. This is observed in the signals shown by Chihi *et al.* (2023), especially in samples 50%-REC, 20%-REC, and 20%-HON. Gary (2014) indicates that if a maximum stress of 50 MPa is reported using steel bars, difficulties may arise in the precise measurement of the

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incident force due to the cancellation of incident and reflected waves. Therefore, it is advisable to validate the dynamic equilibrium of the tests conducted by Chihi *et al.* (2023), especially in samples that do not exceed maximum stresses of 50 MPa. However, if it is desired to keep the same bar material, it is recommended to use a hollow transmitted bar to increase the amplitude of the transmitted pulse. Nonetheless, the most appropriate approach is to change the bars to materials with lower mechanical impedance, such as aluminum, titanium, or magnesium (Hughes *et al.*, 2013; Liao & Chen, 2018; Song & Chen, 2005).

Finally, it is advisable to conduct tests with the same conditions of density and filling pattern of the CF-PETG but modifying printing parameters such as extruder or bed temperatures, printing speed, layer height, or orientation to identify how these variables affect the dynamic properties of CF-PETG.

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