12th International Conference on Composites Testing and Model Identification
J. Varna (Editor)
Riga, 2024

EFFECT OF PLY THICKNESS ON INTERLAMINAR FRACTURE TOUGHNESS OF THIN-PLY THERMOPLASTIC COMPOSITES

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Keywords: hydrogen, permeation, thermoplastic, thin-ply, composites

ABSTRACT

Motivated by the need to mitigate climate change, hydrogen as a CO_2-free alternative to fossil fuels has been on the horizon for decades. While the successful solution to the future energy and climate crisis will obviously rely on multiple technologies and approaches, complementing each other to achieve continuous and grid-optimized energy supply [1], hydrogen-based technologies are essential as they are versatile enough for many applications, ranging from light personal vehicles, powering of habitation units as well as aerospace and aeronautical applications [2]. A main challenge in the hydrogen supply chain is the storage and transportation due to its high diffusivity and corrosivity to metals. Four storage vessel types are well developed, while the most efficient in use today is type IV, where carbon fiber composite (CFRP) is wrapped over a polymeric liner. Type V tanks, fully CFRP without liner, was proposed during the last decade as a lighter tank and overcome the challenges of type IV tanks that include the liner cavitation and collapse. Despite their advantage, the high permeation rate due to matrix cracks and first ply failure due to accumulation of hydrogen at the interface (similar phenomenon to the liner collapse) are still challenges that limit their application in ground vehicles and storage units [3]. In this work, we propose thin-ply thermoplastic composites that over come both challenges of type V tanks, where matrix cracking was supressed and the interlaminar fracture toughness of the laminate interfaces was enhanced by activating extrinsic dissipation mechanisms during propagation such as fiber and ply bridging.

The material used in this study is CF reinforced polyamide 6 (CF/PA6) with ply 42 µm ply thickness. Three staking sequences were consolidated with different layer thickness at the delamination interface: $[0_{90}/90_3/0_3//]s$, $[0_{90}/90/0/90_2/0_2//]s$, and $[0_{90}/90/0/90/0/90/0//]s$. These configurations are composed of a core of cross plies and supporting layer of 0 plies to enable the double cantilever beam testing (DCB). The three laminates were nominated as thick-layer, intermediate-layer and thin-layer laminates with layer thickness of 126, 84 and 42 µm, respectively. The material was consolidated at fast cooling rate of 40 °C/min, as recommended by the supplier. A pre crack of 50 mm was created during manufacturing by inserting a PTFE film of 10 µm thickness at the mid interface. DCB tests were performed following ASTM D5528 standard at 1mm/min loading rate. The mode I fracture toughness, and the effective crack length was calculated using Hashemi et al. [4] closed-form solution, wherein the beam compliance was computed using the simple beam theory.

Figure 1 illustrates the load-displacement response of three laminates, the calculated fracture toughness as a function of effective crack length, and the corresponding macroscopic damage modes. Among the three laminates, the thin-layer laminate exhibited nearly 50% higher fracture toughness compared to the thick-layer laminates. The macroscopic damage modes shown in **Figure 1(c)** revealed significant differences in ply bridging. In the thick-layer laminate, a single ply bridging was observed, with the main crack (yellow arrow) and crack migration to the $0_3/90_3$ interface (blue arrow). For the intermediate-

layer laminate, two ply migrations were identified at the $0_2/90_2$ and 90/0 interfaces. In contrast, the thin-layer laminate displayed three ply migrations. This increased ply migration in the thin-layer configuration led to greater energy dissipation due to the creation of a larger crack surface area at the 0/90 interfaces. Additionally, the formation of a ply bridge between the delaminated and upper interfaces contributed further to the increase in fracture toughness. Fiber bridging at the 0/0 interface was observed across all three laminates. However, the fracture toughness did not scale directly with the number of ply bridges. While the intermediate-layer laminate exhibited a 16% increase in toughness compared to the thick-layer laminate, the thin-layer laminate demonstrated a 34% higher toughness than the intermediate-layer laminate. This disparity can be attributed to differences in matrix crystallinity. The thin-layer laminate exhibited a lower crystallinity (28.5 ± 2.1%) compared to the thick- and intermediate-layer laminates (33.6 ± 0.22%). The reduced crystallinity in the thin-layer laminate results from restricted crystal growth in the out-of-plane direction due to the presence of perpendicular fibers. In contrast, thick-layer laminates contain larger resin-rich regions that facilitate crystal growth during consolidation. The thin-layer laminate demonstrated superior interface toughness compared to both thick-layer laminates and thermoset composites. This enhanced toughness effectively delays the onset of first-layer delamination, making the thin-layer laminate a promising choice for use in Type V tanks.

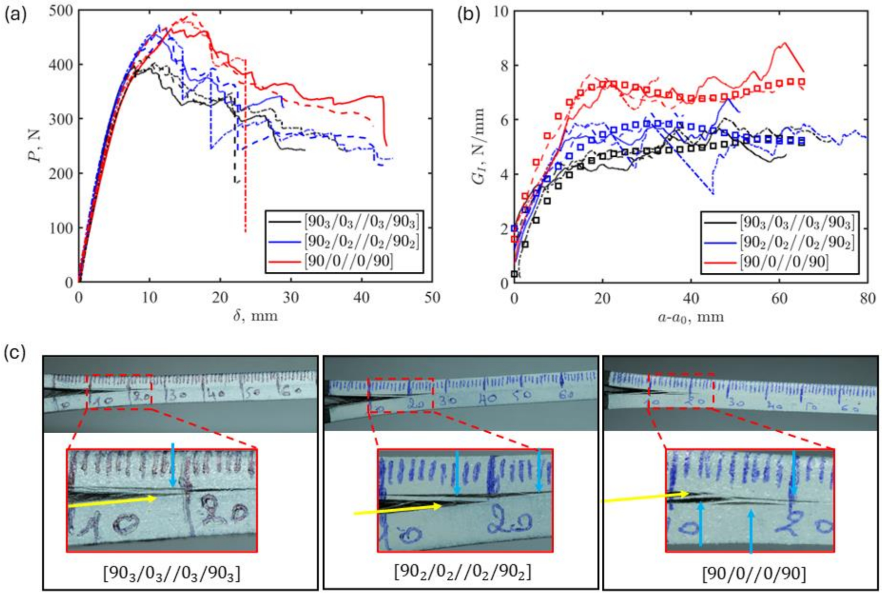

Figure 1: Effect of layer thickness on mode I fracture toughness: (a)load-displacement response, (b) fracture toughness vs. crack length and (c) macroscopic damage modes.

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