

Experimental Investigation on Impact Behaviors of Thermoplastic Polyurethane Composites [†]

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Abstract

This study presents an experimental investigation into the low-velocity impact behaviors of Kevlar/thermoplastic polyurethane (TPU) composite laminates. Using a drop-weight impact apparatus, composite laminates with three different matrix volume fractions were subjected to impact energies ranging from 10 J to 50 J. A high-speed camera has been utilized to capture dynamic deformation morphology. The impact behavior of TPU composite is featured by smooth mechanical response histories with the absence of severe failure or fiber breakage, even at high energy level. Findings also reveal that increasing TPU matrix content can enhance the laminate impact stiffness, which is coherent with elevated peak force and reduced deformation. Notably, deformation morphology characterizes recoverable wrinkles on the rear-side surface underscoring the enhanced damage tolerance of laminates due to the large deformation. The findings are significant for the design of safer, more resilient composite structures, highlighting the potential application of TPU-based laminates in the fields.

Keywords: soft composite; low-velocity impact; Kevlar; TPU; circular fixture

1. Introduction

Composite materials are increasingly employed in aerospace, and other fields with lightweight structures, due to their high strength and stiffness [1,2]. However, a well-known drawback of laminated composites is their vulnerability to impact damage, which can induce internal delamination and matrix cracks that drastically affect the structural integrity [3]. Even low-velocity impacts (LVI) can cause barely visible impact damage that significantly diminishes the material's strength [3]. This concern has driven extensive research into improving the impact resistance and damage tolerance of composites [4–6]. In this context, thermoplastic matrix composites have recently gained attention as a promising alternative, offering superior fracture toughness, damage tolerance, and re-processability [7,8].

Thermoplastic polymers show recyclability and repairability, while thermoplastic prepreps also have practically unlimited shelf life and do not require freezer storage, simplifying handling and reducing material waste [9]. Beyond chemical advantages, thermoplastic composites are distinguished by their ability to undergo plastic deformation and fiber-bridging effects under load, which enhances energy absorption and inhibits



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crack propagation [10,11]. Thermoplastic-matrix laminates tend to be tougher and more impact-resistant than thermoset ones. Shah et al. [12] found that glass fiber thermoplastic composite required higher impact energy to initiate damage than the equivalent thermoset one. The matrix ductility in thermoplastics allowed localized plastic deformation and prevented extensive crack growth, whereas the brittle epoxy facilitated larger delamination damage. Many studies have been conducted on elucidating the mechanical properties and damage mechanisms of various thermoplastic composites under impact [13–15]. For instance, Mohsin et al. [13] evaluated the impact responses of two types of fiber-reinforced laminated composites with different thermoplastic matrices, polyamide and polyphenylene sulphide, and found that they responded similarly at low impact energies, but at higher energy levels, polyamide laminates exhibited less initial deformation than the other type. Hazzard et al. [14] examined the effect of fiber architecture on the impact behavior of thin polyethylene composite laminates. They found that cross-ply laminates exhibited the largest back-face deflection, whereas quasi-isotropic ones can reduce central deflection. Chen et al. [15], in their study, investigated the impact properties and interfacial strength of polyethylene plain woven composites with different thermoplastic matrix content. They addressed that by reducing the matrix volume fraction, the interfacial strength would decrease, leading to a decline on maximum stress and increase on maximum strain.

Thermoplastic polyurethane (TPU), as a segmented copolymer, is a recently developed versatile elastomeric thermoplastic with advanced application potential owing to its microphase-separated structure giving it superior performance on high elongation at break, elastic resilience, and abrasion resistance [16]. TPU can impart exceptional toughness and flexibility to composites; recent studies have indeed begun to examine TPU composite systems [17–19]. Rizzo et al. [17] conducted a comparative study on TPU-coating composite and demonstrated that TPU can significantly enhance the composite's impact resistance by altering energy absorption mechanisms and mitigating damage propagation, observing undamaged samples even under high-energy impacts. Russo et al. [18] investigated impact responses of glass-fiber TPU laminates and reported no interlayer delamination, demonstrating TPU's toughening performance. Miller et al. [19] incorporated a thin TPU interleaf between plies of a carbon/epoxy laminate to enhance a fan blade leading edge. The additional TPU interlayer led to notably smaller damage zones under impact, substantially increasing the impact damage tolerance of the structure [19]. Based on the existing evidence, TPU composites have demonstrated considerable promise as materials with enhanced impact resistance, necessitating further investigation into its impact characteristics and response mechanisms.

In view of the aforementioned considerations, this study presents an experimental investigation into the impact behavior of Kevlar fiber-reinforced TPU matrix composites under low-velocity impact conditions. Utilizing a drop-weight impact testing apparatus, impact tests were performed at three distinct energy levels on TPU composites featuring three different matrix volume fractions. Comprehensive analysis has been conducted to examine the mechanical responses and damage morphologies exhibited by these TPU composites. The primary objective of this research is to enrich the limited knowledge on impact behavior of TPU-matrix composites. The findings and results will help to clarify the TPU's effect on impact resistance and damage tolerance, thereby guiding their future development for impact-critical applications.

2. Material

The reinforcement in this study is Kevlar® XP S307 fabric, (305 g/m², thickness 0.27 mm, 440 tex), supplied by DuPont Brasil (Barueri, São Paulo, Brazil). It consists of two layers of parallel fibers, superimposed, stitched together, and oriented at $\pm 45^\circ$ angles.

The fabric structure schematic and surface morphology are depicted in Figure 1. Mantoflex® 2198A thermoplastic polyurethane (TPU), supplied by Mantoflex Indústria de Plásticos Ltd.a. (Caxias do Sul, RS, Brazil), was used as the matrix material. This material was initially received as pellets, with a density of 1.23 g/cm³, Shore hardness 98A, and a melt flow rate of 4.5 g/10 min (205 °C/2.16 kg). Prior to processing, the TPU pellets were dried at 105 °C for 5 h, subsequently extruded into TPU films (areal density: 60 g/m², average thickness: 60 µm). To enhance the homogeneity and crystallinity of TPU, these films underwent an additional annealing at 80 °C for 8 h.

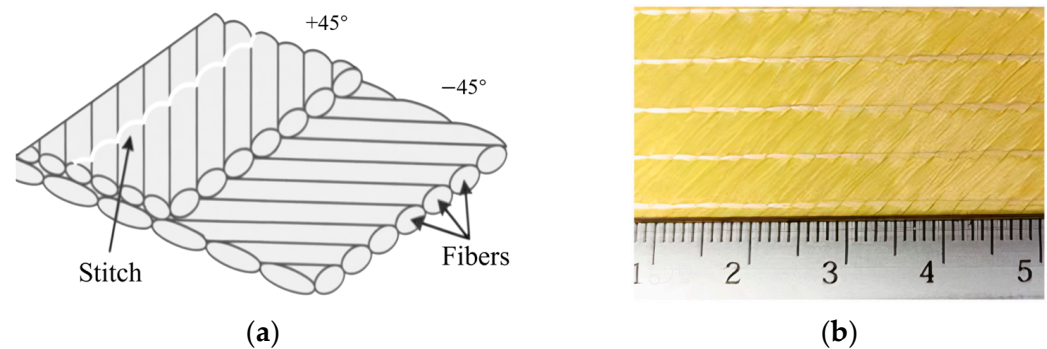


Figure 1. The bi-layer aramid fabric: (a) a schematic illustration of the fabrication; (b) real surface photographic image.

Previous research has explored various techniques for integrating matrices with fibers, including prepregging [20], film calendaring [21], dry powder impregnation [22], aqueous suspension methods [23], etc. Among these approaches, hot press forming [24,25], adopted in this study, is one of many prominent and efficient manufacturing processes used in thermoplastic composite manufacturing with its straightforward implementation procedure. In this study, TPU composite laminates were fabricated by employing a hydraulic press model. Initially, stacking fabrics with annealed TPU films were precisely organized according to the designed configurations and put between 200 °C heated mold plates. The molds were then closed, and a pressure of 10 MPa was applied. After maintaining these conditions for a predetermined duration, the press model was opened, and the laminate was transferred to an oven for post-processing. Solidification was completed through curing at 80 °C for 15 h. Three distinct laminate configurations with varying TPU matrix contents were designed and fabricated, the laminate stacking sequences and statistic details are presented in Figure 2 and Table 1. In the sample nomenclature adopted, the letter ‘K’ designates the Kevlar aramid layers, while ‘PU’ refers to the TPU films. Each laminate consists of 8 aramid fabric intercalated by 1, 2, or 3 layers of TPU films. Cross-sections were prepared along the thickness direction, followed by examination using optical microscopy to reveal meso-structure characteristics, as shown in Figure 2, where the darker regions as aramid fabric and the lighter regions as TPU matrix.

Table 1. Summary of the laminates.

Laminates	Aramid Layers	TPU Film Layers	Thickness (mm)	Matrix Volume Fraction
K8_1PU	8	7	2.44	13.9%
K8_2PU		14	2.85	29.9%
K8_3PU		21	3.16	38.1%

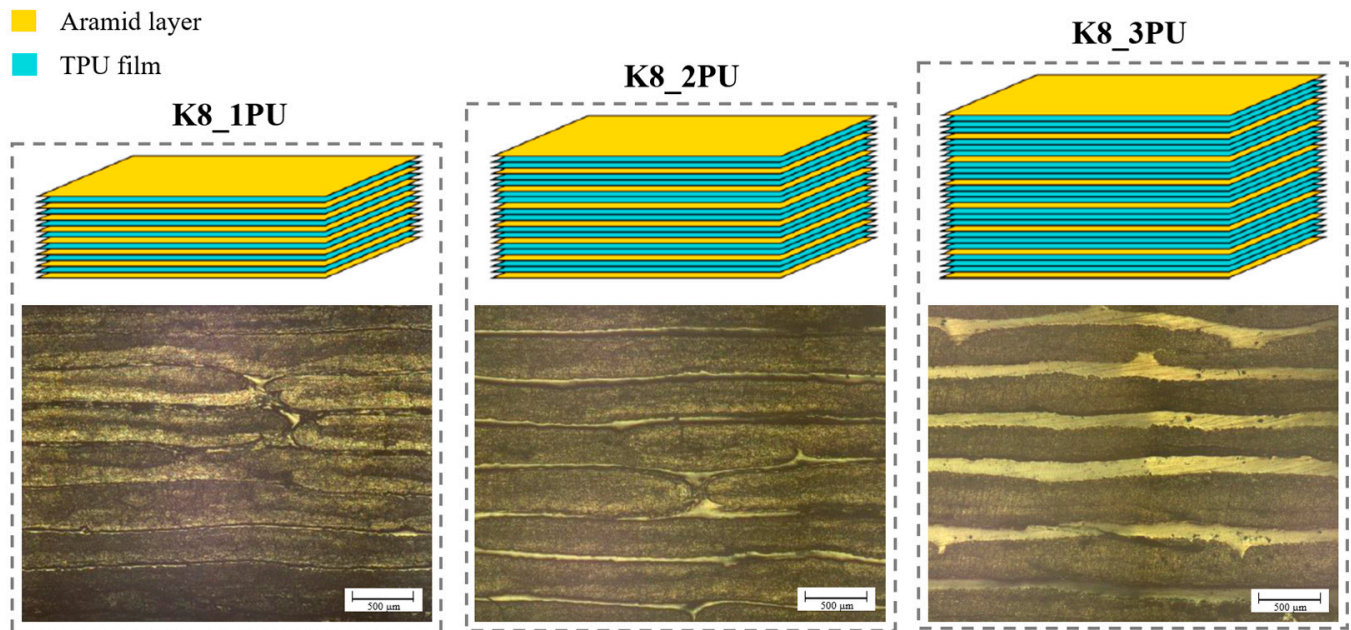


Figure 2. Illustration of the studied laminate configurations and optical microscopy images of laminates on cross-section.

3. Experiment

As illustrated in Figure 3, low-velocity impact tests were conducted according to ASTM D7136 standards [26] utilizing a drop tower apparatus with a different fixture way. Rectangular specimens measuring 150 mm × 100 mm were impacted centrally using a hemispherical impactor with a diameter of 12.7 mm and a mass of 5.47 kg. A sensor was employed to capture and measure the impact velocity at initial contact between impactor and laminate, and a load cell recorded the contact force. Three distinct impact energy levels, 10 J, 20 J, and 50 J, were applied in this study, with two replicates performed for each testing condition. To avoid multiple unintended impacts, a pneumatic arm was activated during each test. Specimens were securely fixed using a circular clamp featuring a central aperture of 75 mm diameter. This clamp employed four rubber grips, applying pressure around the specimen to ensure stable positioning. Impact parameters, including impactor velocity, displacement, and energy absorption, were calculated using force data from the load cell and velocity measurements from the sensor. Additionally, dynamic behaviors of the laminates during the impacts have also been captured by using a high-speed camera capable of recording at 3000 frames per second. Due to constraints from the fixture base and experimental components located above the specimen, imaging was performed from the rear side of the laminate. To effectively capture clear images of specimen deformation, a mirror was positioned beneath the specimen at a 45-degree angle relative to the specimen plane, as depicted in Figure 3. The high-speed camera was horizontally mounted, and supplementary illumination was used to enhance visibility. This arrangement facilitated direct vertical imaging of the rear surface morphology, enabling detailed in situ observation of specimen behavior throughout the impacts.

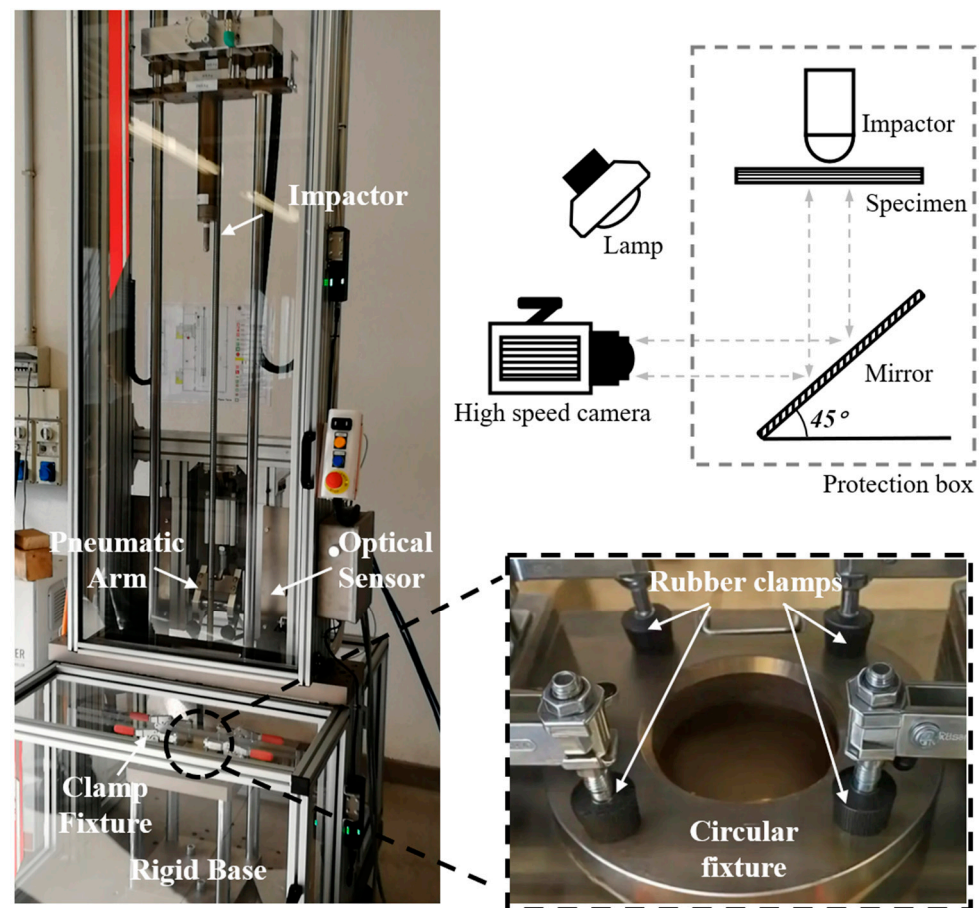


Figure 3. Illustration of experiment setup.

4. Result and Discussion

This section summarizes and discusses the results obtained from impact tests at different energy levels, encompassing the mechanical response histories, key impact metrics and damage morphologies. Figures 4–6 present a summary of mechanical responses histories from low-velocity impact tests at 10 J, 20 J and 50 J respectively, illustrating force-displacement, force-time and absorbed energy-time relationships. Table 2 provides a summary of key metrics on mechanical response, including maximum displacement, final displacement, peak force, and energy absorption percentage.

Table 2. Experiment results on key metrics for impact cases across different energies.

Impact energy	Peak Displacement (mm)			Final displacement (mm)		
	K8_1PU	K8_2PU	K8_3PU	K8_1PU	K8_2PU	K8_3PU
10 J	10.06	9.51	8.52	1.66	1.47	0.93
20 J	13.31	13.07	11.02	5.75	4.56	3.64
50 J	20.95	19.47	17.12	13.92	11.65	9.23
Impact energy	Peak force (N)			Energy absorption percentage (%)		
	K8_1PU	K8_2PU	K8_3PU	K8_1PU	K8_2PU	K8_3PU
10 J	2346.1	2607.8	2859.2	43.5	39.5	34.6
20 J	3571.2	3888.3	4067.9	63.5	59.8	55.8
50 J	5696.4	6454.4	7011.7	84.3	80.7	76.1

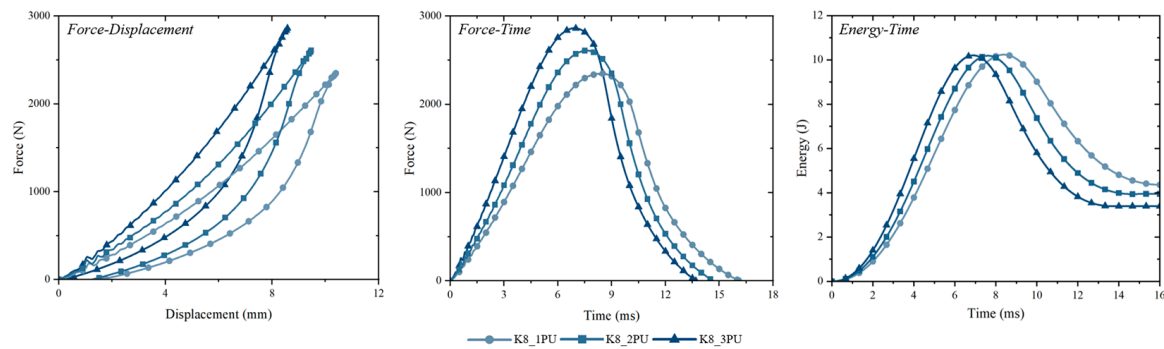


Figure 4. Result of mechanical response histories at 10 J impact.

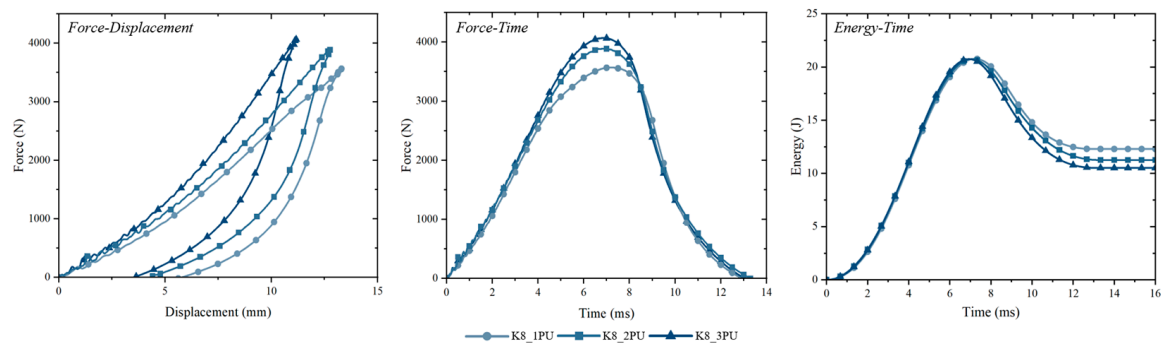


Figure 5. Result of mechanical response histories at 20 J impact.

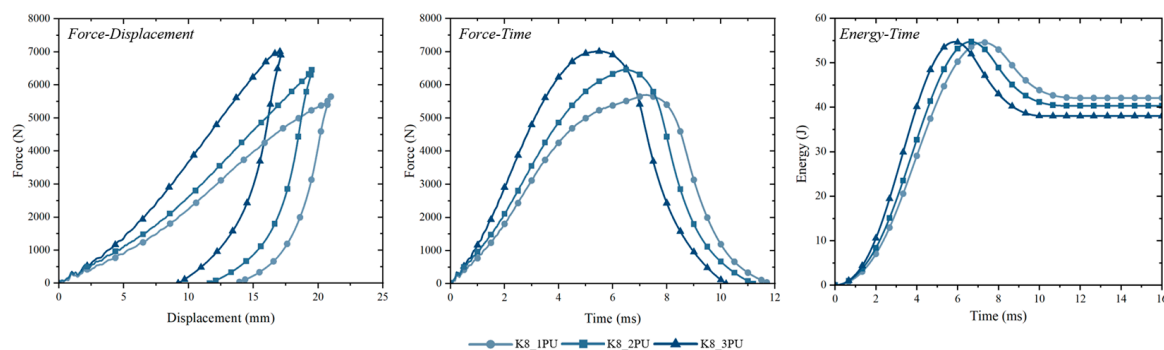


Figure 6. Result of mechanical response histories at 50 J impact.

From the force-displacement and force-time plots, it firstly can be observed that across all the impact energy levels ranging from 10 J to 50 J, the response curves remain smooth in all cases, without occurring significant oscillations or abrupt reductions on force variation throughout the displacement or time histories. This indicates the absence of composite failure or notable damage at all TPU laminate configurations in all impact cases. Moreover, smooth force-displacement curves displayed closed shape over all the impact energy levels, referring all laminates with various TPU content that exhibited dynamic deformation followed by rebound without penetration under all impact cases. This accordingly reflected on the energy-time relationship where the laminate absorbed all the impactor's kinetic energy and then released portions of it during deformation recovery. These mechanical response behaviors demonstrate the superior toughness and ductility characteristics of the thermoplastic composites which attributes to TPU elongation and elasticity inherent properties as matrix material.

Upon further observation of the mechanical response together with key metrics information in Table 2, it is evident that across all three impact cases, as the TPU content increases in laminate, from K8_1PU to K8_3PU, the slope of the ascending segment on the

force-displacement curves becomes steeper, signifying an enhancement on the laminate's stiffness. This increase in stiffness is accompanied by elevated peak forces, reduced maximum displacement and also the final displacement. Meanwhile, from the perspective of the force-displacement curves, the areas enclosed by the curves shrink, indicating the reduction in energy absorption of the laminate under identical impact condition. Considering the influence of TPU content, starting from K8_1PU with the lowest matrix fraction volume, the incorporation of additional TPU films increases both the matrix fraction and the total thickness of laminate, contributing to the enhancement and stiffening of the laminate. As a result, elevating the TPU content can effectively enhance the impact stiffness under varying impact conditions.

On the other hand, through observation and comparison of the mechanical responses under varying impact conditions across Figures 4–6, several critical trends are evident. As the impact energy level increases, the final displacement, representing plastic deformation of the laminates, progressively grows, accompanied by an enhanced proportion of absorbed energy. Furthermore, the discrepancy in final displacement among laminates with different TPU matrix contents also becomes increasingly pronounced with rising impact energy. This phenomenon underscores the amplified influence of TPU content on the laminate's displacement at elevated energy levels. Specifically, under the 10 J impact scenario, laminates with all configurations exhibit minimal differences in final displacement, quantified as approximately 1 mm, as detailed in Table 2.

In addition to the analysis and discussion on mechanical response, this study also includes the damage morphology together with the dynamic deformation behavior of TPU composite under impacts. Figures 7–9 displays the deformation morphology of laminate within all types of configurations from the back side view at 10 J, 20 J and 50 J respectively, on both dynamic peak displacement stage and final stage, representing the impact and rebound period. From morphologies, it can be observed that the laminates underwent no failure at all of the three energy levels, even at 50 J impact, and across all composite configurations, even for K8_1PU with the lowest TPU content. The images provide a direct visualization of the deformation processes occurring in laminates under impact loading, including the formation of impact bulge and subsequent rebound recovery. This visually substantiates the hypotheses in previous mechanical response analyses. As impact energy increases from Figures 7–9, the dynamic structural deformation of the laminates intensifies significantly together with more pronounced final plastic deformation. Additionally, comparison under identical impact energy conditions clearly reveals that increasing the TPU content progressively mitigates the degree of laminate deformation, evident from reduced maximum impact bulge and final deformation, which aligns with the previously identified mechanical response trends.

Wrinkles, emerging as a distinctive deformation feature on TPU-matrix composites under impacts, is rarely encountered in composites with conventional brittle epoxy resin [5], highlighting the exceptional toughening capabilities imparted by TPU as matrix material. During impact loading, a prominent linear wrinkle emerges on the backside of the laminate, crossing the impact center at an approximate angle of 45°. This wrinkle progressively extends during impact loading and partially retracts during the subsequent rebound phase associated with structural recovery. Specifically, in scenarios with pronounced dynamic deformation, such as the K_1PU laminate under 20 J impact conditions shown in Figure 8, and all laminates at 50 J impacts presented in Figure 9, additional wrinkles aligned along and perpendicular to the stitch directions become evident around the primary wrinkle. Attributed primarily to the outstanding ductility, elasticity, and toughness inherent to TPU, the formation of recoverable wrinkles is more likely driven by localized non-uniform tensile stresses on the laminate surface. Concurrently, microscale and mesoscale hetero-

geneities arising from the woven structure of aramid fibers integrated with stitching might also introduce different frictional interactions, contributing to wrinkle formation. As a result, the observed minor damage and plastic deformation across the broad spectrum of impact energies in composite laminates with varying TPU contents underscore the substantial toughening efficacy of TPU as matrix material, which can significantly enhance the composite system's damage tolerance and consequently improve overall impact resistance performance.

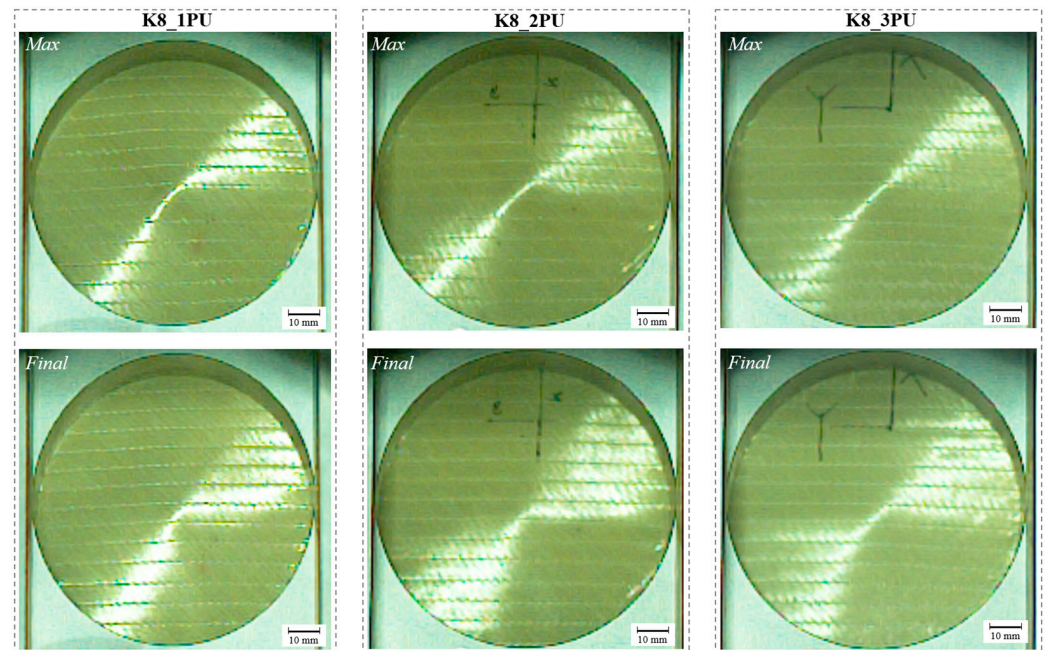


Figure 7. Morphology of TPU composite laminate's deformation on two key stages of 10 J impact: Maximum displacement and Final displacement.

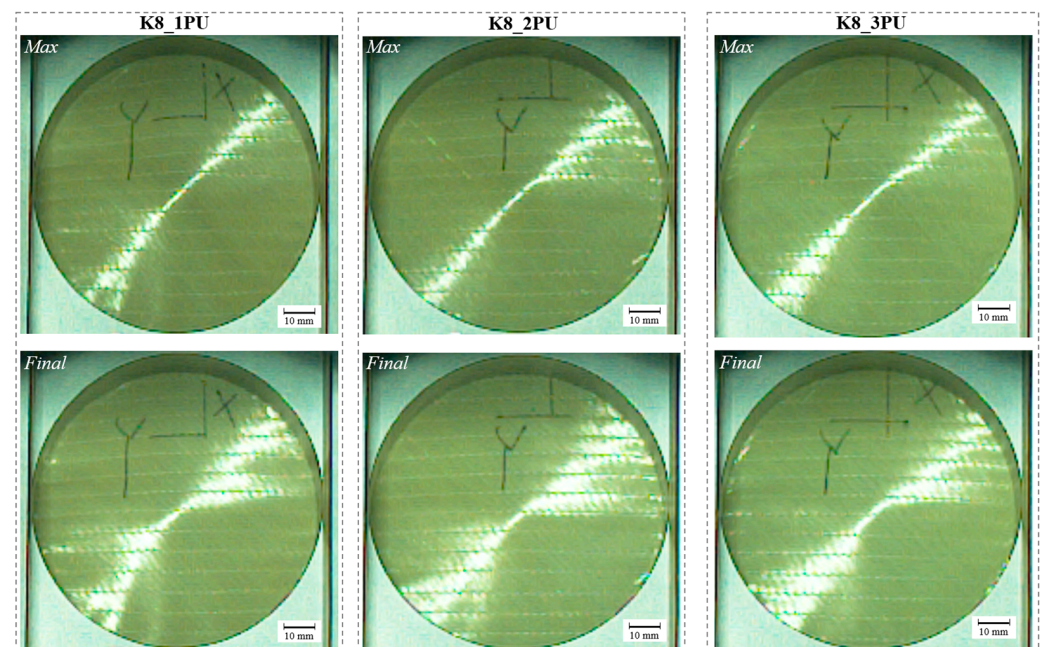


Figure 8. Morphology of TPU composite laminate's deformation on two key stages of 20 J impact: Maximum displacement and Final displacement.

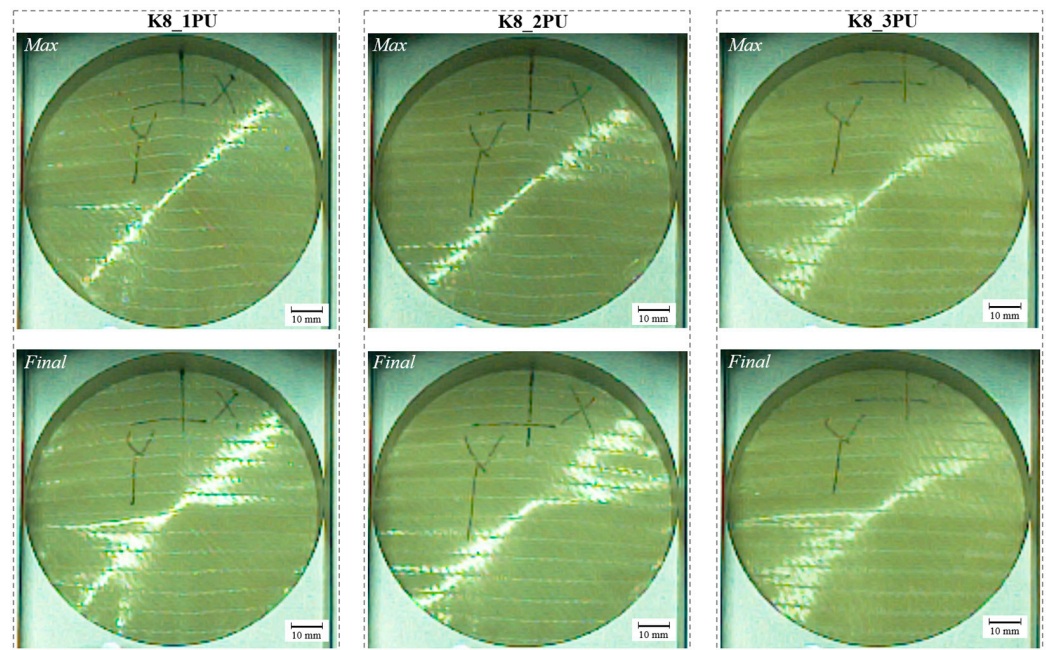


Figure 9. Morphology of TPU composite laminate's deformation on two key stages of 50 J impact: Maximum displacement and Final displacement.

5. Conclusions

In this paper, this study presented a detailed experimental investigation into the low-velocity impact behavior of Kevlar aramid fiber-reinforced TPU-matrix composites, with focus on the mechanical response and deformation morphology. In summary, the findings underline that the composites exhibit superior impact resilience and damage tolerance across all configurations with various TPU content over broad range of impacts, emphasizing the TPU-based composite substantial promise for impact-critical applications. The main conclusions from this study include:

- All laminate configurations exhibited excellent impact resistance, evidenced by smooth response histories and absence of severe damage or failure, demonstrating TPU's toughening effect on enhancement of composite damage tolerance;
- Within laminate, increasing TPU content can significantly enhance the structural impact stiffness, accompanied by elevated peak force, reduced maximum deflection and residual deformation, while improving impact energy dissipation;
- Recoverable wrinkle deformation emerged prominently on the laminate's rear surface under impact loadings, particularly evident at higher energy levels orientating along characteristic angles, highlighting TPU's superior ductility and elasticity.

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