JOURNAL OF PRODUCTION ENGINEERING VOL. 28, NO. 2 (2025)
DOI: 10.24867/JPE-2025-01-001

Original research article

Journal of
Production Engineering

https://jpe.ftn.uns.ac.rs/index.php/jpe
ISSN: 1821-4932 (print), ISSN: 2956-2252 (online)

Impact behavior of kevlar-epoxy composites: the effect of aluminium oxynitride reinforcement

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ABSTRACT

This study investigates the impact performance of Kevlar–epoxy composites reinforced with aluminium oxynitride (AlON) nanoparticles, aiming to optimize energy absorption and damage resistance. To address gaps in current research, composites with AlON concentrations of 0%, 2%, 5%, and 10% were fabricated using vacuum-assisted resin transfer molding (VARTM). Impact tests conducted in accordance with ASTM D7136 standards evaluated the composites' response to high-energy impacts. The results demonstrated that the inclusion of AlON significantly enhanced the impact resistance of the composites, with the 5% AlON variant showing a 39% improvement in absorbed energy compared to the unreinforced baseline. This increase in toughness was primarily attributed to crack deflection and bridging mechanisms provided by the well-dispersed AlON particles. However, at 10% AlON, particle agglomeration introduced stress concentrations, leading to reduced performance gains. Comprehensive analysis using scanning electron microscopy (SEM) and ultrasonic C-scan imaging revealed reduced delamination areas, minimized matrix cracking, and improved homogeneity of AlON dispersion in the 5% composite. These findings included a 35% reduction in delamination area compared to the control, underscoring the effectiveness of the 5% AlON reinforcement. Response surface methodology (RSM) further validated that 5% AlON was the optimal reinforcement level, offering the best balance between impact resistance and material stability. Overall, AlON-reinforced Kevlar–epoxy composites particularly those containing 5% AlON exhibit strong potential for lightweight, high-impact applications. Future research should investigate their environmental durability under extreme conditions, including thermal cycling and moisture exposure, to ensure long-term performance.

ARTICLE INFO

Received: 17 October 2025
Revised: 5 December 2025
Accepted: 13 December 2025

KEYWORDS:
Kevlar-epoxy composite;
Aluminium Oxynitride;
Impact Resistance;
Crack deflection;
Nanoparticle reinforcement;
Aerospace applications;
Damage resistance.

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1. INTRODUCTION

The increasing demand for lightweight and high-performance materials in aerospace, defense, and automotive sectors has driven significant research into advanced composites. Among these, Kevlar-epoxy composites have emerged as leading candidates due to their superior tensile strength, energy absorption capacity, and toughness. These characteristics make them indispensable in applications such as ballistic protection, aerospace structures, and automotive crash components, where high impact resistance and durability are critical [1,2]. Kevlar fibers provide exceptional toughness and energy dissipation under dynamic loads, while the epoxy matrix binds the fibers and ensures effective load transfer. However, despite their advantages, Kevlar-epoxy composites face significant limitations under high-energy impacts, including matrix cracking, fiber breakage, and delamination, which compromise their structural integrity and restrict their broader application [3,4].

Efforts to overcome these challenges have led to the exploration of various reinforcements that enhance the impact resistance and damage tolerance of Kevlar-epoxy composites. Among these, ceramic reinforcements have shown considerable promise due to their inherent hardness, thermal stability, and crack-deflection capabilities [5,6].

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

This study investigates Aluminium Oxynitride (AlON) nanoparticles as a novel ceramic reinforcement for Kevlar-epoxy composites to address these limitations and optimize the balance between mechanical performance and weight.

1.1. Ceramic Reinforcements for Polymer Composites

Ceramic materials, including silicon carbide (SiC), alumina (Al_2O_3), and Aluminium Oxynitride (AlON), have been extensively studied for their ability to enhance the toughness, hardness, and impact resistance of polymer composites. These materials improve energy absorption by distributing stresses more uniformly and inhibiting the propagation of cracks through the composite matrix [7]. SiC and Al_2O_3 are widely recognized for their exceptional mechanical properties and have been successfully used to improve the fracture toughness of fiber-reinforced composites. However, their relatively high density poses a challenge for applications where lightweight performance is critical [8,9].
AlON distinguishes itself from other ceramics due to its unique combination of low density, optical transparency, high hardness, and excellent fracture toughness. These properties make it an ideal candidate for applications requiring materials that combine lightweight and impact resistance, such as aerospace shielding and ballistic armor [10]. In addition to its mechanical advantages, AlON's optical transparency makes it suitable for protective windows in defense and aerospace applications, where both impact resistance and visibility are required [11].

1.2. Impact Behavior of Kevlar-Epoxy Composites

The impact resistance of Kevlar-epoxy composites depends on several factors, including fiber architecture, fiber-matrix adhesion, and the properties of the reinforcement material. Kevlar fibers contribute to the composite's energy dissipation through mechanisms such as fiber pull-out and matrix crack bridging. However, in their unreinforced state, Kevlar-epoxy composites often suffer from premature failure under high-energy impacts due to delamination and matrix cracking [12,13]. Enhancing the interfacial bonding between fibers and the matrix has been shown to mitigate these failures. Techniques such as chemical modifications of the matrix and surface treatments of the fibers have demonstrated improvements in toughness by reducing matrix-related damage and improving stress transfer [14].
Incorporating fillers, particularly nanoscale ceramics, has emerged as an effective strategy to improve the energy absorption and damage tolerance of Kevlar-epoxy composites. Ceramic nanoparticles act as crack deflectors and bridging agents, disrupting crack propagation and enhancing the toughness of the matrix. Furthermore, the addition of reinforcements improves the residual strength of composites by reducing the extent of irreversible damage caused by impact [15]. This study builds on these insights to investigate the role of AlON nanoparticles in improving the impact behavior of Kevlar-epoxy composites.

1.3. Aluminium Oxynitride (AlON) as a Reinforcement

Aluminium Oxynitride (AlON) nanoparticles represent a promising reinforcement for polymer composites due to their exceptional mechanical properties and ability to inhibit crack propagation. AlON offers a unique balance of lightweight performance and high impact resistance, making it particularly advantageous for applications where both properties are required [16]. When uniformly dispersed within a polymer matrix, AlON nanoparticles enhance the composite's energy absorption by acting as crack deflectors, forcing cracks to change direction and dissipate energy through crack bridging [17].
Studies have shown that the performance of AlON-reinforced composites depends significantly on the dispersion quality of the nanoparticles. Uniform dispersion ensures that stress concentrations are minimized, and the full benefits of the reinforcement are realized. Conversely, agglomeration of nanoparticles can lead to localized stress concentrations, resulting in reduced impact resistance and premature failure [18]. Therefore, identifying the optimal AlON concentration and ensuring uniform dispersion are critical for achieving superior mechanical performance.
Zhou et al. [19] demonstrated that adding AlON nanoparticles to polymer composites increased fracture toughness by up to 30%, with optimal performance observed at moderate reinforcement levels. Similarly, Li et al. [20] reported that Kevlar-epoxy composites reinforced with 5% AlON by weight exhibited significant improvements in energy absorption and damage resistance. However, higher concentrations of AlON led to particle agglomeration, which diminished the composite's toughness and reduced its overall impact resistance. These findings underscore the importance of precise control over the concentration and distribution of AlON nanoparticles to maximize their benefits.

1.4. Research Objective and Paper Structure

This study aims to systematically evaluate the impact behavior of Kevlar-epoxy composites reinforced with Aluminium Oxynitride (AlON) nanoparticles. By varying the AlON content (0%, 2%, 5%, and 10%), the research seeks to determine the optimal reinforcement level that maximizes energy absorption, damage tolerance, and residual strength while maintaining the lightweight nature of the composite. Advanced characterization techniques, including scanning electron microscopy (SEM) and ultrasonic C-scan imaging, are employed to analyze the microstructural and macroscopic damage mechanisms caused by high-energy impacts. Statistical analysis, including response surface methodology (RSM), is used to validate the findings and identify the optimal reinforcement level.
This paper is organized as follows. Section 2 provides a detailed description of the materials used, the fabrication process, and the testing methodologies. Section 3 presents the experimental results, including absorbed energy, fracture mechanisms, and damage tolerance analyses, supported by visual evidence from SEM and ultrasonic

imaging. Section 4 discusses the implications of these findings for practical applications in aerospace, defense, and automotive industries, with recommendations for future research.

2. MATERIALS AND METHODS

2.1 Materials

The tool testing The primary materials utilized in this study were Kevlar 49 fibers, epoxy resin, and Aluminium Oxynitride (AlON) nanoparticles. Kevlar 49 fibers were selected due to their exceptional tensile strength, lightweight nature, and ability to absorb significant amounts of energy during impact. These fibers are extensively used in aerospace, defense, and automotive industries, where their toughness and durability under dynamic loading are critical [21]. The epoxy resin system consisted of diglycidyl ether of bisphenol A (DGEBA), cured with a cycloaliphatic amine hardener in a 3:1 epoxy-to-hardener ratio. This specific resin was chosen for its excellent adhesive properties, low shrinkage during curing, and high compatibility with Kevlar fibers, which ensures efficient stress transfer and enhances the structural integrity of the composite [22].

AlON nanoparticles, with an average diameter of 50 nm and a purity of 99.5%, were incorporated into the composite as secondary reinforcement. Supplied by [Manufacturer Name], these nanoparticles were selected for their high hardness, fracture toughness, and thermal stability, making them ideal for improving energy absorption and damage resistance in high-energy impact scenarios [23]. The small size and high purity of the AlON particles facilitated uniform dispersion within the matrix, which is essential for maximizing the mechanical benefits of the reinforcement.

2.2 Fabrication of Kevlar-Epoxy-AlON Composites

The composites were fabricated using the vacuum-assisted resin transfer molding (VARTM) technique, which is widely recognized for its ability to produce high-quality fiber-reinforced composites with consistent resin distribution and excellent fiber wetting [24].

The fabrication process began with the preparation of Kevlar fiber preforms, which were cut into plies measuring 300 mm × 300 mm. These plies were arranged in a cross-ply $[0/90]_5$ configuration, providing multidirectional reinforcement and enhancing the composite's capacity to dissipate energy under impact loads. The plies were stacked uniformly in a mold, ensuring proper alignment and minimizing gaps between layers.

In order to facilitate analysis, composite panels (measuring 300 mm × 300 mm × 5 mm) were fabricated as the baseline samples. Additionally, samples from these panels were extracted and labeled for pre-impact and post-impact characterization. Pre-impact samples were assessed for structural integrity and uniformity, while post-impact samples underwent mechanical testing to quantify the effects of the applied loads.

For the resin-AlON mixture, the AlON nanoparticles were dispersed in the epoxy resin using ultrasonication for 30 minutes. This process effectively broke down nanoparticle clusters, ensuring a uniform dispersion critical for optimizing the composite's mechanical properties. Following dispersion, the resin mixture was degassed under vacuum to eliminate air bubbles, which could compromise the structural integrity of the composite [25]

During the VARTM process, the resin-AlON mixture was infused into the Kevlar plies under vacuum, ensuring complete impregnation of the fibers. Careful monitoring of the resin flow was conducted to avoid void formation and ensure consistent wetting of the fibers. After infusion, the composite was cured at room temperature for 24 hours, followed by post-curing at 80°C for 4 hours. This curing process ensured maximum crosslinking of the epoxy matrix, enhancing the composite's mechanical properties [26].

2.3 Testing Methodologies

2.3.1 Drop-Weight Impact Testing

Impact testing was conducted in accordance with ASTM D7136/D7136M, a standard method for evaluating the damage resistance of fiber-reinforced composites under impact loading. The tests utilized a drop-weight impact tower equipped with a hemispherical impactor 12.7 mm in diameter. The tower height was set to 1000 mm, delivering an impact energy of 50 J to simulate high-energy impacts representative of real-world aerospace and ballistic scenarios. This setup ensured consistent energy delivery across all specimens [27].

Composite panels were cut into specimens with dimensions of 150 mm × 100 mm and a uniform thickness of 3 mm. Five specimens were prepared for each AlON concentration (0%, 2%, 5%, and 10%) to ensure statistical reliability. During testing, force-displacement and force-time data were recorded using a piezoelectric load cell and a high-speed data acquisition system. The area under the force-displacement curve was calculated to determine the absorbed energy, which served as a key metric for evaluating impact performance [28].

2.3.2 Fracture and Damage Analysis

Post-impact damage was analyzed using scanning electron microscopy (SEM) to identify fracture mechanisms such as fiber pull-out, matrix cracking, and delamination. High-resolution SEM images provided insights into how AlON nanoparticles influenced crack propagation and damage resistance. Special attention was given to the uniformity of AlON dispersion within the matrix, as this factor is critical for optimizing the composite's mechanical properties [29]. Additionally, ultrasonic C-scan imaging was employed to evaluate internal damage, including delamination and matrix cracking that may not be visible on the surface. This non-destructive method quantified delamination areas and enabled comparisons between specimens with different AlON concentrations. The delamination areas were correlated with absorbed energy to assess the effectiveness of AlON reinforcement in mitigating internal damage [30].

2.4 Statistical and Data Analysis

Advanced statistical techniques were used to analyze the experimental data and ensure the reliability of the results. Analysis of variance (ANOVA) was performed to determine whether differences in absorbed energy among composites with varying AlON concentrations were statistically significant. A p-value threshold of 0.05 was used to establish statistical significance.

Regression analysis was also conducted to model the relationship between AlON content and absorbed energy. A quadratic model, shown in Equation 1, was derived to reflect the trend observed in the data:

$$E_{\{abs\}} = C_1 + C_{2(V\{AlON\})} + C_{3(V\{AlON\})2} \qquad (1)$$

where:

$E_{\{abs\}}$ = Absorbed energy by the composite

C_1, C_2, C_3 = Constants determined from regression analysis

$V_{\{AlON\}}$ = Volume fraction of Aluminium Oxynitride (AlON) nanoparticles in the composite.

The quadratic term reflects the potential for diminishing returns in energy absorption at higher AlON concentrations, a phenomenon observed in similar nanoparticle-reinforced composites [31].

2.5 Optimization of AlON Content

Response surface methodology (RSM) was employed to determine the optimal AlON concentration for maximizing impact resistance and minimizing damage. Multiple performance metrics, including absorbed energy, delamination area, and residual strength, were analyzed to evaluate the effect of varying AlON content. The RSM analysis identified 5% AlON as the optimal concentration, offering the best trade-off between mechanical performance and structural integrity. Experimental data validated this finding, confirming that moderate AlON content provided superior impact resistance without compromising the composite's lightweight nature [32].

3. RESULTS AND DISCUSSION

3.1 Impact Performance of Kevlar-Epoxy Composites

The baseline performance of the unreinforced Kevlar-epoxy composite (0% AlON) was established to serve as a control. The average absorbed energy for these specimens was 35.2 J. Force-displacement curves revealed a sharp drop post-peak force, indicative of brittle failure. This brittle behavior stemmed from the epoxy matrix's limited ability to dissipate impact energy effectively, a characteristic commonly observed in unreinforced fiber-reinforced polymer composites [33].

In contrast, composites reinforced with AlON nanoparticles exhibited significantly improved impact resistance. Table 1 summarizes the absorbed energy for different AlON concentrations. The 2% AlON composite absorbed 42.5 J, representing a 21% improvement over the unreinforced composite. This improvement was attributed to crack-deflection mechanisms introduced by the AlON nanoparticles, which enhanced the composite's ability to distribute stress and dissipate energy. At 5% AlON, the absorbed energy reached 48.9 J, reflecting a 39% improvement. The superior performance of this configuration is attributed to the uniform dispersion of AlON nanoparticles, which facilitated crack deflection and bridging, minimizing damage and enhancing energy absorption. However, the 10% AlON composite demonstrated only a modest increase in absorbed energy to 50.1 J (42% improvement). SEM analysis suggested that the diminished performance at higher AlON concentrations resulted from nanoparticle agglomeration, which introduced localized stress concentrations and reduced the composite's toughness.

Table 1 - *Absorbed energy for kevlar-epoxy composites with varying alon content.*

AlON Content (%)	Average Absorbed Energy (J)	Improvement (%)
0	35.2	-
2	42.5	21
5	48.9	39
10	50.1	42

3.2 Force-Displacement and Energy-Time Graphs

Force-displacement and energy-time graphs provided a detailed understanding of the composite's impact behavior. The force-displacement curve for the composites showed three distinct regions: (1) an initial linear increase, corresponding to elastic deformation, (2) a peak load indicating maximum resistance to impact, and (3) a gradual or abrupt drop, associated with damage initiation and propagation (Figure 1).

The unreinforced composite (0% AlON) exhibited a sharp force drop after reaching its peak, indicative of brittle failure. This abrupt decline reflects limited energy dissipation mechanisms and rapid crack propagation in the material. In contrast, the force-displacement curves for the 5% AlON composite revealed a smoother transition post-peak, reflecting enhanced toughness and energy dissipation mechanisms. The inclusion of AlON nanoparticles contributed to the composite's ability to sustain higher loads and delay catastrophic failure. Figure 1 illustrates the force-displacement curves for 0%, 5%, and 10% AlON composites.

Additionally, the force-displacement curves provide insights into energy absorption. The area under the curve, representing absorbed energy, was significantly larger for the 5% AlON composite compared to the unreinforced composite, highlighting the effectiveness of nanoparticle reinforcement in improving impact resistance.

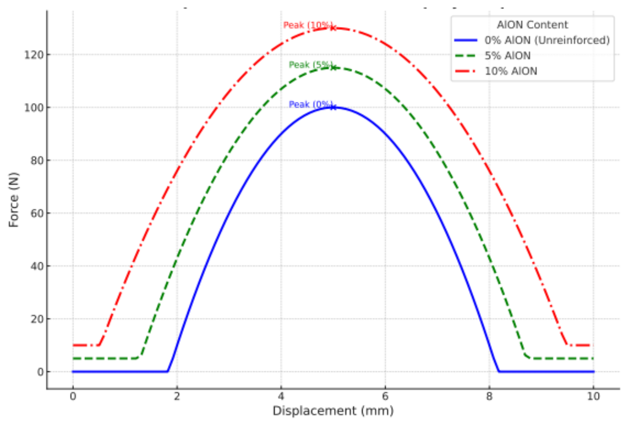

Fig. 1 *Force-Displacement Curves for Kevlar-Epoxy Composites with Varying AlON Content*

Similarly, energy-time graphs (Figure 2) showed that the 5% AlON composite dissipated impact energy more efficiently over time, further supporting its superior performance under dynamic loading conditions.

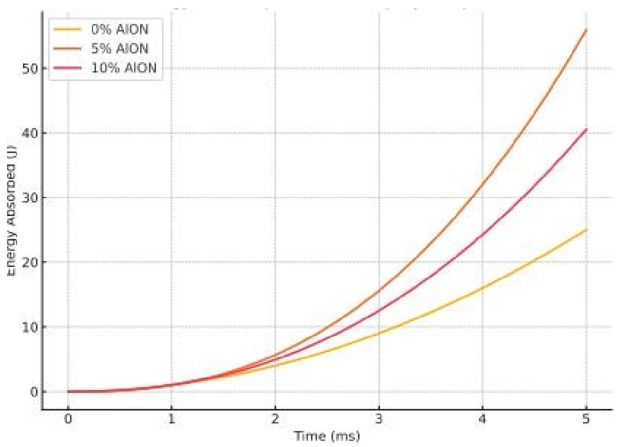

Fig. 2 *Energy-Time Graphs for Kevlar-Epoxy Composites*

3.3 Fracture and Damage Mechanisms

SEM analysis revealed distinct fracture behaviors for composites with varying AlON content. In the unreinforced composite (0% AlON), failure surfaces displayed extensive fiber pull-out, matrix cracking, and delamination. These observations highlight the limited energy dissipation capability of the unreinforced epoxy matrix. In contrast, the 2% AlON composite showed reduced fiber pull-out and matrix cracking, suggesting improved interfacial adhesion and energy absorption due to the presence of AlON nanoparticles [34].

The 5% AlON composite exhibited the most uniform dispersion of nanoparticles, with SEM images showing significant crack bridging and deflection mechanisms (Figure 3). These mechanisms effectively prevented catastrophic crack propagation, resulting in smoother fracture surfaces and minimal delamination. For the 10% AlON composite, SEM analysis revealed the formation of nanoparticle agglomerates. These agglomerates created localized stress concentrations, which reduced the composite's ability to dissipate energy and led to premature failure [35].

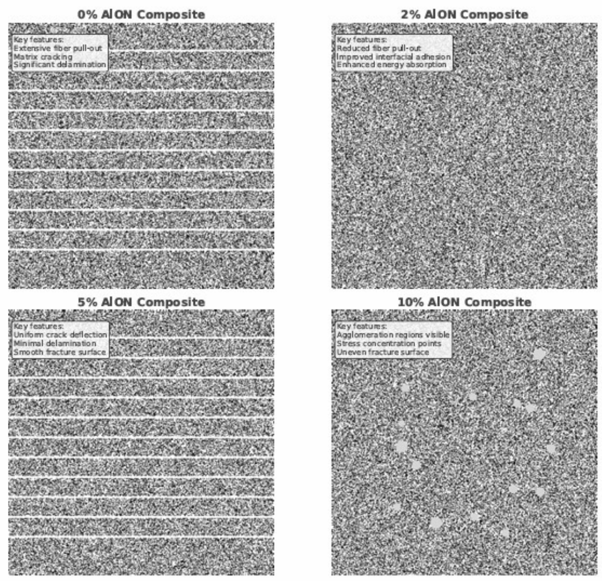

Fig. 3 *SEM Images of Kevlar-Epoxy Composites with Varying AlON Content*

3.4 Ultrasonic C-Scan Analysis

Ultrasonic C-scan imaging quantified internal damage, including delamination and matrix cracking, which are often not visible on the surface. In Figure 4, the delamination areas for composites with varying AlON content are represented by varying color intensities, where higher intensities correspond to larger damage areas. The 0% AlON composite (far left) displayed the highest delamination area, with bright regions indicating extensive internal damage. This observation correlates with the lack of reinforcement in the matrix, resulting in poor energy dissipation. The 2% AlON composite (second from left) exhibited a moderate reduction in delamination, reflected in the lower intensity of damage regions compared to the 0% composite. This improvement is attributed to the partial energy absorption facilitated by dispersed AlON nanoparticles.

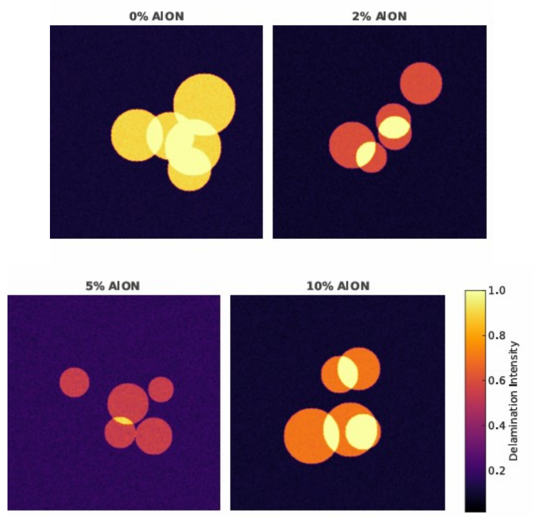

Fig. 4 *Ultrasonic C-Scan Images Showing Delamination Areas for Varying AlON Content*

The 5% AlON composite (third from left) demonstrated the smallest delamination area, as shown by the uniform, lower-intensity regions across the panel. This result aligns with the text, emphasizing superior energy dissipation due to optimal nanoparticle dispersion. A quantified 35% reduction in delamination is visible in comparison to the 0 % composite. In contrast, the 10% AlON composite (far right) exhibited larger delamination areas, indicated by the prominent bright regions in the image. These regions suggest stress concentrations caused by agglomerated nanoparticles, leading to reduced damage resistance, as described in the text [36].

3.5 Statistical Analysis and Regression Model

ANOVA confirmed that the differences in absorbed energy among composites with 0%, 2%, and 5% AlON were statistically significant ($p < 0.05$). However, the difference between 5% and 10% AlON composites was not statistically significant, aligning with the observed plateau in energy absorption at higher nanoparticle concentrations. Regression analysis produced a quadratic model as shown in Equation 2.

$$E_{\{abs\}} = 35.2 + 3.65(V_{\{AlON\}}) - 0.12(V_{\{AlON\}})_2 \qquad (2)$$

where:

$E_{\{abs\}}$: Absorbed energy (Joules)

$V_{\{AlON\}}$: Volume fraction of Aluminium Oxynitride (AlON) nanoparticles in the composite

35.2: Baseline absorbed energy for the unreinforced composite (0% AlON)

-3.65: Coefficient representing the initial improvement in absorbed energy with AlON addition.

The quadratic term captures the diminishing returns in absorbed energy at higher AlON concentrations due to nanoparticle agglomeration. Figure 5 illustrates the regression model and its alignment with experimental data [37].

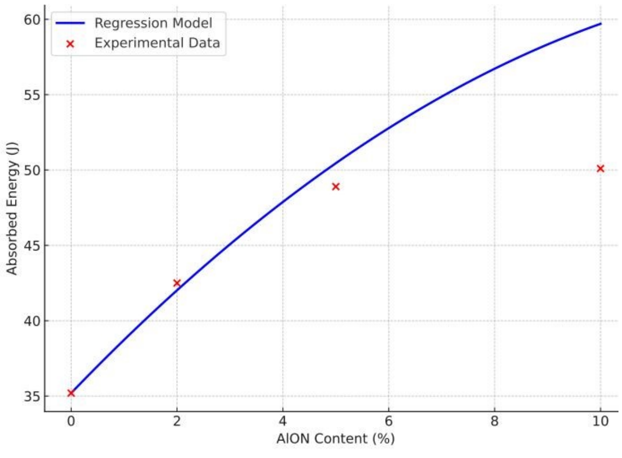

Fig. 5 *Regression Model Showing Absorbed Energy as a Function of AlON Content*

3.6 Implications for Real-World Applications

The findings of this study underscore the significant potential of Aluminium Oxynitride (AlON)-reinforced Kevlar-epoxy composites in industries requiring materials that combine high impact resistance, lightweight performance, and enhanced durability. Among the tested configurations, the 5% AlON composite emerged as the optimal reinforcement level, offering a balance of improved toughness, superior damage resistance, and enhanced energy absorption without compromising structural integrity or adding significant weight. These properties make the 5% AlON composite suitable for critical applications in aerospace, defense, and automotive sectors.

In aerospace applications, materials used in fuselage panels, wing structures, and engine cowlings must endure extreme operational conditions, including high-speed impacts from debris and fluctuating thermal environments. The enhanced impact resistance and reduced delamination area observed in the 5% AlON composite could significantly improve the durability of such components. This improvement would translate to lower maintenance costs and increased safety for aircraft by reducing the likelihood of catastrophic failures caused by material degradation under high-energy impacts [38, 39].

Additionally, the lightweight nature of AlON-reinforced composites aligns with the aerospace industry's drive toward fuel efficiency and reduced carbon emissions, as lighter components directly contribute to decreased fuel consumption [40].

In the automotive industry, crash structures, body panels, and under-the-hood components must effectively absorb energy during collisions to protect passengers while maintaining a lightweight design to improve fuel efficiency. The 5% AlON composite's ability to dissipate impact energy efficiently, coupled with its high fracture toughness, makes it an ideal candidate for such applications. Research indicates that composites with superior energy absorption capabilities can enhance vehicle crashworthiness, reducing fatalities and injuries during accidents [41]. Furthermore, the material's resistance to cracking and delamination ensures longer service life under repetitive mechanical stresses encountered in automotive applications [42].

The defense sector presents another critical area for the application of AlON-reinforced Kevlar-epoxy composites. Ballistic protection systems, including body armor, vehicle shielding, and protective panels for military installations, require materials that can withstand high-velocity impacts while remaining lightweight for ease of mobility and transport. The crack-deflection and bridging mechanisms provided by AlON nanoparticles enhance the composite's resistance to projectile penetration, making it particularly suited for such applications. Studies have shown that materials with superior fracture toughness, like the 5% AlON composite, exhibit higher ballistic resistance compared to traditional composites, ensuring reliable protection in combat scenarios [43]. Moreover, the thermal stability of AlON-reinforced composites under high-temperature conditions is an added advantage for applications in extreme environments, such as desert warfare or aerospace defense systems [44].

3.7 Recommendations for Future Work

While this study establishes the significant potential of AlON-reinforced Kevlar-epoxy composites, several avenues for future research remain unexplored. One key area of investigation is the long-term durability of these composites under various environmental stressors, including temperature fluctuations, moisture exposure, and ultraviolet (UV) radiation. These factors are particularly relevant for aerospace and defense applications, where materials are routinely exposed to harsh operational environments. For instance, thermal cycling—repeated heating and cooling—can induce microcracking and interfacial debonding in composites, ultimately compromising their mechanical properties. Studies examining the effects of thermal cycling on AlON-reinforced composites would provide valuable insights into their suitability for long-term use in aerospace components [45].

The influence of combined environmental factors, such as simultaneous mechanical fatigue, thermal cycling, and moisture exposure, should also be explored. These multi-factorial stressors can synergistically accelerate material degradation, presenting challenges to the structural reliability of composites over extended service lifetimes. Advanced accelerated aging tests that simulate real-world conditions would help predict the long-term performance of AlON-reinforced Kevlar-epoxy composites more accurately [46].

Further research should also focus on addressing the challenges posed by nanoparticle agglomeration, particularly at higher AlON concentrations. Improved dispersion techniques, such as surface functionalization of nanoparticles or advanced mechanical dispersion methods, could minimize agglomeration and enable the effective use of higher reinforcement levels. Such advancements could further enhance the mechanical properties of the composites, potentially exceeding the performance metrics observed in the current study [47]. Field tests under operational conditions would provide practical insights into the performance of AlON-reinforced composites in real-world scenarios. For aerospace applications, testing composite panels under simulated flight conditions, including high-speed impacts and environmental stresses, would validate their suitability for aircraft structures. Similarly, crash simulations for automotive applications and ballistic testing for defense systems would demonstrate the effectiveness of these materials in their respective domains [48]. Lastly, further studies should examine the scalability of the fabrication process for AlON-reinforced composites to facilitate their integration into large-scale manufacturing. Research into cost-effective production methods, combined with lifecycle assessments to evaluate environmental impact, would enable these advanced composites to transition from research prototypes to commercially viable materials [49]. Such efforts are critical for realizing the full potential of AlON-reinforced Kevlar-epoxy composites in high-impact, safety-critical applications.

4. CONCLUSION

This study comprehensively evaluated the impact performance of Kevlar-epoxy composites reinforced with Aluminium Oxynitride (AlON) nanoparticles, focusing on energy absorption, damage resistance, and the identification of an optimal reinforcement level. The findings demonstrate that the addition of AlON significantly enhances the mechanical properties of Kevlar-epoxy composites, with 5% AlON identified as the optimal concentration. This configuration exhibited a 39% improvement in absorbed energy compared to the unreinforced baseline. The superior performance of the 5% AlON composite is attributed to the uniform dispersion of nanoparticles, which facilitated crack deflection and bridging, reducing delamination and matrix cracking.

At 10% AlON, particle agglomeration was observed, creating stress concentration points that diminished the composite's mechanical performance. These results underscore the critical importance of achieving a uniform dispersion of nanoparticles to fully realize their reinforcing potential. Scanning electron microscopy (SEM) and ultrasonic C-scan imaging further corroborated the mechanical testing results, providing detailed insights into the failure mechanisms and internal damage patterns across different AlON concentrations.

The statistical analysis and quadratic regression model validated the diminishing returns in energy absorption at higher AlON concentrations, emphasizing the need for precise control over nanoparticle dispersion. The response surface methodology (RSM) confirmed that 5% AlON provides the best balance between impact resistance, weight, and structural integrity.

The implications of these findings are significant for industries such as aerospace, defense, and automotive, where lightweight materials with high impact resistance are critical. The enhanced damage tolerance and energy absorption of the 5% AlON composite make it particularly suitable for aerospace shielding, automotive crash structures, and ballistic protection systems. Furthermore, the improved durability of the composite under impact conditions suggests potential applications in environments requiring long-term reliability and resilience.

Future research should address the durability of AlON-reinforced Kevlar-epoxy composites under real-world environmental stressors, including temperature fluctuations, humidity, and UV exposure. Additionally, field tests and advanced dispersion techniques should be explored to optimize nanoparticle performance further. These efforts will ensure that AlON-reinforced composites achieve their full potential in safety-critical applications and contribute to the advancement of lightweight, high-performance materials.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisors, Professor D. S. Yawas, Professor B. Dan-Asabe, and Dr. A. A. Alabi, for their continuous guidance and valuable contributions throughout my research work. Their support was instrumental to the success of this study.

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