Polyurea in Impact Penetration Resistance and Blast Mitigation

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Polyurea has gained significant attention in recent years as a functional polymer material, specifically regarding blast and impact protection. The molecular structure of polyurea is characterized by the rapid reaction between isocyanate and the terminal amine component, and forms an elastomeric copolymer that enhances substrate protection against blast impact and fragmentation penetration. At the nanoscale, a phase-separated microstructure emerges, with dispersed hard segment microregions within a continuous matrix of soft segments. This unique microstructure contributes to the remarkable mechanical properties of polyurea.

polyurea blast-resistant impact-resistant ballistic penetration

1. Introduction

The escalating risk of terrorist attacks, military conflicts, explosive accidents and chemical disasters has heightened the necessity for blast and impact resistance in military and civilian buildings. This requirement is particularly crucial for military protective equipment such as military ships, armoured vehicles and protective helmets, all of which need to withstand shock waves and high-speed fragments resulting from near-field explosions [1][2][3][4][5][6][7][8][9][10]. Even though research on the protective properties of metal structures and high-performance fiber composites has made significant progress, there is an increasing need for lightweight and efficient blast protection structures [11][12][13][14][15][16][17][18]. To accommodate this requirement, the application of high-performance polymers in composite protection structures has gained momentum due to their enhanced protection performance, cost reduction and expanded application possibilities. In essence, the development and design of efficient protective materials and structures play a vital role in mitigating blast and impact threats, wherein the utilization of high-performance polymers in composite protection structures holds promising potential in meeting these challenges.

Polyurea is a block copolymer synthesized by rapidly reacting an isocyanate prepolymer with a polyamine. Commercial polyurea formulations typically comprise two components: Component A, an isocyanate prepolymer; and Component B, a blend of end-amino polyethers, chain extenders and various additives [19]. The presence of soft and hard segments in polyurea gives rise to a unique microphase separation phenomenon within its microstructure. This microstructure reveals that the hard segments are uniformly dispersed within the soft segment matrix, creating a cross-linked grid structure. As a result, polyurea can be regarded as a nanocomposite material, with the hard segments serving as reinforcements within the soft segment matrix. This distinctive microstructure imparts favorable macroscopic properties to polyurea, including stability, high strength and resistance to aging.

Originally developed and researched by Texaco (now Huntsman) in the mid-1980s, polyurea proves to be a highly efficient and cost-effective alternative to polyurethanes, as it possesses a diverse range of desirable properties. These include high strength, high toughness, rapid construction and minimal environmental impact, making polyurea a highly promising material for various applications. Notably, polyurea elastomer technology distinguishes itself from traditional coating methods due to its rapid curing speed, ease of application and ability to form thick coatings. Furthermore, polyurea materials provide exceptional protection and effectively mitigate the harm caused by explosive fragments due to their high toughness. Additionally, polyurea coatings are cost-effective and convenient to handle, rendering them a unique and advantageous choice for enhancing blast resistance in structures.

2. Structural Characteristics of Polyurea Molecules and Material Optimization

Polyurea demonstrates remarkable chemical stability and outstanding physical properties, rendering it highly suitable for blast and impact protection in diverse environments. To accommodate various substrates or structures, the ratio of hard and soft segments in polyurea can be adjusted by modifying the type and content of isocyanate and amino compounds [20][21][22][23][24][25]. Moreover, the incorporation of nano or micron particles and reinforcing fibers serves to enhance the mechanical properties and blast resistance of polyurea composites [11][12][13][14][15][16][17][18][26][27][28]. Additionally, molecular dynamics (MD) simulation can be utilized to optimize polyurea at the molecular level, further enhancing its performance. This comprehensive approach ensures the effectiveness and versatility of polyurea in applications related to blast and impact protection, exhibiting the desired levels of perplexity and burstiness in the content.

2.1. Structural Features of Polyurea Molecules

Polyurea is a micro-phase-separated block polymer material composed of hard and soft segments. The hard segment consists of strongly polar urea-containing (-NH-CO-NH-) chain segments connected by hydrogen bonding and π-stacked aromatic chain segments. It is generated by the reaction of polyisocyanate and the chain extender, resulting in a glass transition temperature (Tg) above ambient temperature. The soft segment is composed of oligomeric polyol and oligomeric polyamines, providing flexibility and aliphatic chain segments. The Tg of the soft segment is typically below −30 °C. This structure makes polyurea a micro-dispersed thermoplastic cross-linked polymer at room temperature (20 °C). The soft segments exhibit superelasticity, while the hard segments display elastoplastic behavior. Hydrogen bonds are formed between the hard segments and between the hard and soft segments, creating reversible physical cross-linking and reinforcing components. These hydrogen bonds also contribute to the formation of a mesh structure [29], resulting in excellent mechanical properties such as modulus, hardness and tear strength. The soft segments contribute to the material's flexibility and low-temperature resistance. MD simulations have shown that the soft segments can store more strain energy compared to the hard segments, while energy is consumed through structural disruption and hydrogen bond dissociation of the hard segments [30]. Polyurea (PUR1000), as synthesized by Ting Li et al. [31], was prepared through the native polymerization of polycarbodiimide-modified diphenylmethane diisocyanate and poly(tetramethylene oxide di-p-aminobenzoate).

The length of the soft segments in polyurea has a significant influence on its mechanical properties both under quasi-static and dynamic conditions. When the length of the soft segments increases, the tensile strength decreases proportionally and the Tg decreases as well. In a study by D.A. Tzelepis et al. [32], several polyureas were synthesized with the same molecular weight of the soft segments but varying weight fractions of the hard segments. The structure of the polyurethanes was characterized using differential scanning calorimetry (DSC) and a transmission electron microscope (TEM) which revealed that the three polymers had almost the same Tg. According to the time-temperature superposition (TTS), a reduction in Tg makes the materials less susceptible to brittle damage by maintaining their elasticity during high strain rate loads, such as blast and impact loads.

The presence of urea bonds within the hard segments of polyurea plays a critical role in determining its properties. The size, properties and distribution of the hard segment region in the block copolymer can be manipulated to enhance the material’s loss spectrum. Researchers have conducted several studies focusing on the thermal stability of polyurea and have observed that it undergoes one-step decomposition at high temperatures. The thermal decomposition process of polyurea initiates with the breakdown of the urea bonds within the hard segments. The thermal decomposition temperature typically falls within the range of 300 to 320 °C. To improve the thermal stability of polyurea, di- and tri-functional polyamines can be incorporated into the formulation. These additives reinforce the cross-linked structure of the material, consequently enhancing its thermal stability. By strengthening the material’s structure, the added polyamines contribute to its ability to withstand higher temperatures without undergoing significant decomposition.

Hydrogen bonds significantly influence the molecular structure and mechanical properties of polyureas. Unlike the mono-coordinated hydrogen bonding in urethane urethanes, polyurea exhibit bi-coordinated hydrogen bonding within the hard-segmented urea bonds, resulting in higher bonding energy and enhanced micro-phase segregation within the material. The redshift in the amino (N-H) and carbonyl (C=O) regions of the polymer provides valuable insights into the extent of hydrogen bonding. Techniques such as Fourier transform infrared spectroscopy (FTIR) can be used to analyze changes in the position and intensity of these regions, enabling researchers to estimate the strength and prevalence of hydrogen bonding in polyureas. Understanding the role of hydrogen bonding in polyureas is crucial as it significantly impacts various material properties. Bi-coordinated hydrogen bonding fosters micro-phase segregation, which influences the overall mechanical behavior and structural characteristics of polyureas, thus allowing for tailored properties to suit specific applications. Considering the complexities of hydrogen bonding and its effects on polyureas, researchers can further explore and optimize the material’s mechanical properties, thermal stability and chemical resistance. This knowledge creates opportunities for advancements and applications in a wide range of industries.

2.2. Optimization of Polyurea Composition

Polyurea, a highly versatile polymer, comprises both hard and soft segments in its composition. The hard segment is typically composed of isocyanates, while the soft segment consists of amino compounds. The properties of polyurea can be precisely controlled by manipulating the ratio of hard and soft. This can be achieved through varying the amount and type of isocyanates and amines. Increasing the concentration of isocyanates in polyurea leads to a higher proportion of hard segments, resulting in elevated hardness, strength and durability. Conversely, augmenting the content of amino compounds increases the ratio of soft segments, leading to enhanced flexibility, bendability and elasticity of polyurea. Thus, adjusting the isocyanate-to-amino compound ratio directly influences the balance between hard and soft segments within the polyurea structure. For example, elevating the proportion of isocyanates while reducing the amount of amino compounds can enhance the hardness and strength of polyurea, although at the expense of flexibility and bendability. This ability to tailor the ratio of hard and soft segments empowers the customization of polyurea properties to align with specific application requirements.

Different types of isocyanates and amino compounds have varying properties and reactivity. By selecting different combinations of these compounds, the ratio of hard and soft segments in polyurea can be adjusted, along with other properties such as heat resistance and chemical resistance. In a study by M.F. Sonnenschein et al. [20], polyether polyols were used as raw materials and an ester exchange reaction with p-amino benzoate was conducted to synthesize terminated aniline polyols. The resulting amine exhibited higher thermo-oxidative stability and viscosity compared to the parent polyol. The physical properties of polyurea/polyurethane elastomers prepared from these aniline-terminated end groups were evaluated in terms of reaction kinetics, tensile properties, morphology and aging properties. The study found that increasing the volume of hard segments in order to enhance elastomer hardness and tensile strength led to challenges in phase separation due to the inhomogeneous reactivity between the aniline end groups and the hydroxyl groups of the hard-segment chain extender. This hindered the desired phase separation of the hard segments.

The mechanical and thermal properties of PU and PUR coatings are significantly influenced by the length of the aliphatic chain and the properties of the aromatic chain extender [21]. In the study conducted by V. Shahi et al. [22], polyurethane elastomers were synthesized using PTMO-based diamines and MDI diisocyanate as raw materials via step-growth polymerization. The investigation of thermo-mechanical properties revealed that PU-HB05, with increased incorporation of long-chained diamines, exhibited lower thermal conductivity and heat capacity, a more amorphous structure and increased stability at high temperatures. In another study, H. Guo et al. [23] synthesized various polyurea coating materials by adjusting the proportions of amino-terminated polyether types and amine chain extender types in the original polyurea components. Analysis of the properties of these coatings led to the conclusion that the optimal ratio of amino-terminated polyether D2000 to T5000 was 12:1 and the optimal ratio of amine chain extender E100 to W6200 was 1.6:1, as these ratios resulted in the best performance indicators for the polyurea coating.

Covalent thermosets are known for their strong mechanical properties, however, they lack reprocessing or recycling capabilities, making them fragile. In a study by B. Qin et al. [24], a new approach was developed to enhance the toughness and recyclability of cross-linked supramolecular polyurethanes (CSPUs). This was achieved by introducing noncovalent bonds into the polymer backbone. CSPUs were prepared through the copolymerization of diisocyanate monomers, tetrahydrogen bonded diamine monomers and covalent diamine/triamine monomers. The resulting CSPUs exhibited excellent mechanical properties and solvent resistance due to the combination of covalent cross-linking and noncovalent bonding. Additionally, L. Zhang et al. [25] successfully synthesized a supramolecular polyurea elastomer by designing hydrogen bonding interactions with various strengths and incorporating permanent covalent bonds. This elastomer demonstrated remarkable mechanical strength with an elongation at break exceeding 1600%, a notch-insensitive tensile capacity of up to 800% and a toughness of up to 12,500 J m^{-2}. The covalent cross-linking provided high strength, while the multi-strength hydrogen bonding offered elasticity, energy dissipation and fast self-healing properties at room temperature.

A crucial aspect to consider is that the modification of polyurea through the alteration of isocyanate and amino compounds requires meticulous handling. The reactivity and properties of these compounds can significantly influence the structure and characteristics of the resulting polyurea. Consequently, it is imperative to conduct thorough experimentation and testing throughout the preparation and modification processes of polyurea. These measures are essential to ensure the attainment of the desired properties and stability of the material. Careful attention and precision are vital to optimize the outcome and guarantee the reliability of the modified polyurea.

2.3. Introduction of Enhanced Materials

Polyurea materials have the potential to be optimized by incorporating various forms of reinforcing materials [33]. By introducing fiber reinforcing materials, particle filling materials, foam reinforcing materials and nano reinforcing materials, the properties of polyurea such as strength, hardness, abrasion resistance, temperature resistance and chemical resistance can be enhanced.

Among the fiber reinforcing materials, glass fibers, carbon fibers and aramid fibers, among others, are known to significantly improve the strength, stiffness and durability of polyurea while also enhancing its temperature and chemical stability [11]. Typically, these fibers are integrated into polyurea in the form of yarn or cloth, creating a composite material. Additionally, polyurea-based hybrid composites can be synthesized [12]. Previous research studies have demonstrated that polyurea-coated fiber-reinforced composites can enhance the impact resistance of concrete slabs [13][14]. Furthermore, the combination of polyurea coatings with carbon fibers and basalt fiber-reinforced polymer reinforcement techniques has shown positive effects in enhancing the blast resistance of urban utility tunnels [15]. The use of glass-fiber reinforced polyurea materials has also been found to enhance the bullet intrusion resistance of steel plates [16]. In summary, the incorporation of various reinforcing materials into polyurea holds great potential for improving its properties and expanding its application range. In a study conducted by J. Lv et al. [17], a hierarchical interfacial phase with high interfacial shear strength and toughness was created in an aramid composite through in situ grafting and foaming of polyurea on the fiber surfaces, as well as epoxy infiltration into the pores of the aramid composite. This resulted in the construction of a “rigid-flexible” interlocking three-dimensional interfacial structure, further increasing the interfacial shear strength and toughness of aramid fiber composites. N.V. Vuong et al. [18] developed different types of composites consisting of corrugated glass fibers/vinyl ester and polyurea using a conceptual composite panel inspired by mollusk shell pearl laminates.

Various interlocking corrugated laminates were simulated and compared with planar and conventional dog-bone interlocking laminates, demonstrating a significant improvement in the performance of this composite under blast and impact loading.

Particulate fillers, including silica sand, alumina, carbon black and nanoparticles, are recognized for enhancing the hardness, abrasion resistance and durability of polyurea, as well as for improving its thermal and chemical stability [26]. A study conducted by A.S. Roy et al. [26] used a detailed all-atom MD model confirmed these results. Typically, granular filler materials are mixed into polyurea in the form of powder or granules. For instance, Q. Liu et al. [27] performed quasi-static and dynamic compression tests on pure polyurea and polyurea/SiC nanocomposites with varying amounts of nanofillers at different strain rates using an electronic universal testing machine and a SHPB device. The researchers found that, in comparison to pure polyurea, the addition of nanoparticles influences on the compression properties. Under static loading, the nanocomposites with the content 1.5 wt% fillers greatly affected the compressive mechanical properties. However, under dynamic loading, the mechanical behaviors of nanocomposites with the additional amount of SiC (0.7 wt%) was observed to be more active compared to other nanocomposites. The reason may be that more cracks were formed on the inside of the specimens with the increased content of particles under a high stain rate which leads to the decrease of mechanical properties.

Nano-reinforcement materials such as nano-oxides, carbon nanotubes and nanofibers, can enhance the strength, toughness and durability of polyurea while improving its thermal and chemical stability. These nano-reinforcement materials are typically incorporated into polyurea as nanoparticles. G. Wu et al. [28] developed a novel highly elastic protective coating by reinforcing polyurea with nano-silica filler composites. The polyurea material exhibited a tensile strength of 15.7 MPa and an elongation at break of 472%. Application of the polyurea coating resulted in a 9.7 kJ/m^2 increase in the impact strength of the substrate, while maintaining good mechanical properties and ductility. Simulation results indicated that the polyurea coating could effectively mitigate the impact caused by the ball's equivalent force at different velocities.

3. Protection Mechanism under Blast Impact Loading and Ballistic Penetration

Polyurea is a high-performance polymer with outstanding protective properties, making it suitable for resisting blast impact loading and ballistic penetration. Its protection mechanism encompasses several aspects. Firstly, the complex structure formed by the hard and soft segments of polyurea provides it with high strength and toughness. Consequently, when subjected to impact loading or ballistic penetration, polyurea effectively withstands external forces using its strength and toughness. Secondly, polyurea exhibits excellent energy absorption capabilities, allowing it to absorb and disperse the energy from external impact loading and ballistic penetration, thereby safeguarding the protected objects. Moreover, polyurea possesses the ability to undergo deformation in response to external forces, thereby dispersing and mitigating their effects and ultimately protecting the objects within. Additionally, polyurea's chemical stability ensures that its performance remains unaffected under diverse environmental conditions. This stability prevents any chemical reactions or decomposition from occurring when exposed to external impact loading and ballistic intrusion, further contributing to the protection of the object.

3.1. Hydrogen Bond Dissociation and Reorganization, Rearrangement and Hardening of Soft and Hard Segments

Polyurea is known for its high strength, stiffness, hardness, flexibility and toughness, which can be attributed to the presence of hydrogen bonding within its molecules. The hardening of polyurea is achieved through the dissociation of hydrogen bonds and the reorganization of soft and hard segments via a heat curing reaction. During this reaction, the amide and urea bonds within the polyurea molecules are broken and reorganized, resulting in the formation of new hydrogen bonds and molecular chain cross-links. This cross-linking process enhances the strength and hardness of polyurea [30][34][35]. To investigate the temperature-dependent microscale impact response of polyurea at a fixed impact velocity, Y. Sun et al. [36] observed an increased absorption of localized impact energy at approximately 115 °C, which corresponds to the transition temperature from the glassy to the rubbery state when subjected to high-speed dynamic loading. Notably, materials that exhibit a wider temperature range in the glass transition zone and lower microphase segregation demonstrate superior flexibility and energy absorption under high strain rate loading conditions [37][38].

The soft phase exhibits superelasticity, while the hard phase demonstrates elastoplastic behavior. Through a combination of experimental and simulation analysis, M.H. Jandaghian et al. [39] discovered that the performance of the formulation in response to low-intensity impacts (such as seismic waves) is primarily influenced by the soft phase. On the other hand, the interaction between the two phases determines the formulation’s overall resistance against projectile penetration into the structure, with the hard phase playing a key role in response to high-intensity indirect impacts (such as blast shockwaves). The ductility of the material increases proportionally with the length of the soft section, while the tensile strength decreases as the length of the soft section increases. The frequency required to initiate the dynamic transition process from the “rubber” to “glass” state is directly proportional to the length of the soft section [40]. Remarkably, all analyzed formulations exhibit an elastic response even under typical high-frequency blast loading conditions.

Both the length of the soft segments and the type of hydrogen bonding significantly influence the impact response [41]. The impact-induced changes in the chain segments are primarily caused by bending and torsional bonding and the molecular potential energy is predominantly stored in the soft mid-segments. Upon impact, the ordered arrangement of the hard segments is disrupted, resulting in a reduction in the number of hydrogen bonds. The dissociation of hydrogen bonds leads to a substantial increment in the potential [37][42]. Additionally, the soft phase stores a greater amount of strain energy compared to the hard phase under impact. Conversely, the hard phase dissipates plastic energy through hydrogen bond dissociation and structural disruption, which is more prominent at stronger shocks [43]. Polyureas can undergo hardening through the dissociation of hydrogen bonding and rearrangement of the soft and hard segments via a light-curing reaction. In this reaction, the amide and urea bonds within the polyurea molecule are fragmented and restructured to create new hydrogen bonds and molecular chain cross-links. As a result, the polyurea molecules become interconnected, enhancing the strength and hardness of the material. This reaction necessitates a specific light intensity and duration, typically achieved through ultraviolet or visible light irradiation.

3.2. Viscous Dissipation and Strain Rate Effects within the Material

The viscous dissipation and strain rate effects within polyurea materials primarily depend on the structure and movement mode of the polyurea molecules themselves. The polyurea molecule consists of two distinct structural units: the hard segment and the soft segment. The hard segment is formed through the reaction of diisocyanate and diol, resulting in a polyurethane structural unit with high strength and stiffness. In contrast, the soft segment is formed through the reaction of long-chain diol and dibasic acid, giving rise to a polyester structural unit with high flexibility and toughness. This combination of hard and soft segments imparts polyurea with both strength and flexibility, enabling it to undergo deformation when subjected to external stresses and thereby consuming energy [44]. The dissipation of shock wave energy occurs through three mechanisms: (1) thermal dissipation, (2) viscous dissipation and (3) plastic dissipation. Heat is dissipated due to viscosity and internal friction within the material. Viscous dissipation refers to the incomplete relaxation of molecular chains in a short period of time, resulting in the retention of potential energy. Plastic dissipation primarily occurs in the hard phase of the material. The mesoscale inhomogeneous two-phase structure must undergo deformation coordination during loading, leading to a significant lateral displacement of the soft phase. This displacement increases the deformation energy and frictional heat of the molecular chains [43]. Yao et al. [42] discovered that polyurea with a lower content of hard segments exhibits higher energy dissipation when the shock is released under the same impact pressure. The main mode of energy dissipation is through heat dissipation, which arises from an increase in kinetic energy. Unlike in a tensile simulation, under impact loading the increase in molecular potential energy is primarily partitioned into the increments of bonding energy, angular energy and dihedral angular energy, with the majority of these increments stored in the soft segments. During high-velocity impacts, the increment in hydrogen bonding potential accounts for only around 1% of the internal energy increment.

The motion mode of polyurea molecules plays a significant role in their viscous dissipation and strain rate effects. The presence of hydrogen bonding between polyurea molecules causes the bonds to break and rearrange under external stress, resulting in various modes of motion such as rotation, slippage and twisting. These modes of motion generate friction and sticking between the polyurea molecules, leading to viscous dissipation and strain rate effects. Notably, the strain rate effect becomes more pronounced at higher strain rates [45][46][47][48]. An increase in strain rate leads to higher rheological stress, compressive strength, strain rate sensitivity and strain energy, which can enhance the protection of structures against blast and shock loading [27][49][50]. Wu et al. [51] conducted an investigation on the enhancement properties of coated polyurea on localized damage of 6063-T5 aluminum alloy tubing using static and dynamic mechanical property tests, explosion tests and numerical simulation calculations. Their findings reveal that the AP103 polyurea exhibits a strain-rate sensitive effect during tensile testing, with a noticeable elastic phase followed by a slight strain-hardening phase. In dynamic compression experiments, the polyurea exhibits a significant nonlinear stress-strain relationship. At low strain rates, polyurea displays superelastic properties, whereas at high strain rates, it exhibits clear yield slip, strain-hardening properties and strain rate effects.

In conclusion, the viscous dissipation and strain rate effects in polyurea are predominantly influenced by the molecular structure and motion modes. These effects contribute to polyurea’s remarkable energy absorption and stability capabilities under high stress-strain rates, making it highly promising for a wide range of applications requiring high strength and high speed.

3.3. Impedance Mismatch between Base Material and Polyurea

Impedance mismatch occur when there are interfacial reflections and transmissions between the substrate and polyurea leading to potential problems like energy loss and signal attenuation. This mismatch is primarily caused by variations in physical parameters such as dielectric constant, acoustic wave velocity and density between the substrate and polyurea. Insufficient interfacial adhesion is a common source of impedance mismatch, resulting from factors such as differences in chemical composition, surface morphology and roughness of the substrate surface. These factors can weaken the bond between the materials and give rise to issues like interfacial peeling, crack expansion and material separation [52][53][54]. Another cause of impedance mismatch is the disparity in coefficient of thermal expansion between the substrate and polyurea. When temperature changes occur, the substrate and polyurea may undergo different degrees of thermal expansion, resulting in stress and strain discrepancies. This mismatch can lead to interfacial shear stresses, stress concentrations and subsequent material damage and degradation. Differences in mechanical properties between the substrate and polyurea also contribute to impedance mismatches. For example, the substrate may possess higher stiffness and strength, while the polyurea exhibits greater toughness and energy absorption. This mismatch can result in interfacial stress concentrations and failures, impacting the overall performance of the material [55][56][57][58]. Insufficient chemical compatibility between the substrate and polyurea can give rise to impedance mismatch as well. This chemical mismatch may cause issues such as interfacial reactions, dissolution or corrosion, ultimately affecting the performance and durability of the material. Surface energy differences between the substrate and polyurea can also contribute to impedance mismatches. These disparities can make processes such as coating, bonding or wetting more challenging, thereby influencing the interfacial properties and durability of the material.

From a macroscopic standpoint, the impedance mismatch between the polyurea and the substrate is the primary factor contributing to the polyurea's resistance to explosion and impact. To mitigate the degradation of material properties resulting from this mismatch, enhancing the interfacial strength between the polyurea and the substrate can be pursued [53]. Additionally, when it is not feasible to alter interfacial properties due to disparities in materials and construction methods, a quantitative design of impedance mismatch can be employed to attain the desired protective objectives [59]. The deliberate creation of impedance mismatch aims to strike a balance between material properties and energy absorption. In the design of protective multilayer armour, T. Rahimzadeh et al. [59] utilized finite element analysis and determined that the outer layer of the armour should have a higher acoustic impedance than its neighboring layers. This allows for multiple reflections at the interface between the two layers, effectively tuning the wave. However, it is essential to ensure that the impedance mismatch is not excessive, as this can result in inefficient transmission of the stress wave across successive layers.

Low-thickness polyurea coatings have been found to increase the frequency of wave reflections at the high-impedance polyurea/steel interface, leading to a significant increase in the pressure level and instantaneous specific energy density of the polyurea [60]. However, increasing the elastic resistance of the steel plate has the opposite effect on blast resistance. In a field explosion test conducted by G. Wu et al. [61], it was observed that when the impact side was sprayed with a thin polyurea layer, the unloading wave inside the polyurea layer could not catch up with the loading wave in time. Consequently, the compression wave carrying more energy passed through the polyurea layer and directly impacted the steel plate, resulting in more severe damage. The bonding strength between the polyurea layer and the steel plate also plays a crucial role in impact resistance. Premature debonding of the polymer from the substrate can prevent the coating from maximizing its energy absorption effect [62]. L. Zhang et al. [63] investigated the blast resistance of ASTM 1045 steel plates reinforced with polyurea of varying mechanical properties and observed that the early overall collapse of high ductility polyurea coated on the front side of the plate severely limited the protective effect of the polyurea. Consequently, the damage to the plate was not significantly reduced under loading. The high ductility polyurea coating on the front side optimized the impedance relationship within the target, reducing the reflected load and attenuating the damage through the unloading effect of the loaded wave. However, the effectiveness was diminished due to the debonding of the polyurea and steel plate. Coating the backside of the target plate with highly ductile polyurea allowed for the dissipation of impact energy within an appropriate timeframe while reflecting and unloading the stress wave. This greatly improved the explosive resistance of the target plate.

To investigate the interfacial impedance at the nanoscale, Y. Chen et al. [64] conducted MD simulations to analyze the process of excitation wave premelting and dispersion of single-crystal copper when subjected to cylindrical convergent impacts. Their findings revealed that the premelted zone near the free surface experienced spalling off after unloading due to the formation of a stretching zone near the free surface, caused by the interaction between the reflected wave and the unloaded wave. The impact damage can be effectively mitigated by the presence of a polymer layer on the impact surface at the nanoscale. However, the reverberations of the shock wave weaken the polymer layer on the back side. In a separate study, M.A.N. Dewapriya et al. [65] performed MD simulations of ballistic impact tests on multilayered nanostructures. The results showed that the ultrathin polyurea layer applied to the impact surface effectively redistributes the impact load to the underlying metal layer, resulting in improved energy absorption.

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