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Impact of adhesive layer properties on ceramic multi-layered ballistic armour systems: A review

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The role of the adhesive layer in the ballistic performance of ceramic multi-layer armour system is complex and multi-faceted, often with trade-offs between single- and multi-hit performance. However, research focused on untangling the underlying impact of varying adhesive cohesive or adhesion properties is limited and sometimes appears to provide conflicting conclusions. Comparison between the available studies is also often difficult due to variations in armour systems or ballistic testing being conducted. This review scrutinises the available research, identifying six critical properties of an adhesive layer in determining ballistic performance: elastic modulus, fracture strain, acoustic impedance, tensile bond strength, shear bond strength, and thickness. The impact of each of these properties on ballistic performance is discussed in detail, with clear description of the underlying processes involved, allowing clear optimisation goals to be established depending on the ceramic armour specification.

1. Introduction

The use of laminated multi-layer armour systems as a lightweight protective solution, comprising of a ceramic front plate bonded to a metal or fabric-composite backing plate, is an area of extensive research [1,2]. Armour ballistic performance, whilst remaining lightweight, is critically dependent on the constituent material properties, which include, but are not limited to, thickness, elastic modulus, yield strength, density, and fracture toughness [3,4]. The front plate (or strike face) is typically made from ceramic materials, such as alumina, boron carbide, or silicon carbide, which have high compressive strength, but low tensile strength. The ceramic's main role in ballistic protection is the erosion and fracturing of the projectile, possible due to its high compressive strength. The backing plate usually has a high rigidity, supporting the ceramic, compensating for its low tensile strength [4–7]. Typical backing materials include steel, aluminium, aluminium alloys, fabric-composites, or fibre-composites.

The role of the adhesive bonding layer on the ballistic performance is an often overlooked factor when designing lightweight multi-layered armour systems. The adhesives typically utilised are epoxy- or polyurethane-based, with their cohesive properties (bulk mechanical properties), adhesion properties (bonding strength), and layer thickness, typically neglected in armour design and performance considerations. Nevertheless, the adhesive layer plays a multi-faceted role in the ballistic performance and can be a critical factor in determining an armour's single [4–20] and multi-hit [8,12] performance. The adhesive layer should maximise transmission of the stress wave to the backing plate, which is dependent on the impedance mismatch between the ceramic and adhesive [9,13,21]. A large mismatch leads to a high reflection of the compressive stress wave, generating tensile stress on the ceramic plate, creating damage and leading to premature ceramic failure. Secondly, the adhesive should provide a stiff coupling between the ceramic and backing plate. Adhesives exhibiting low compressive modulus and/or high thickness will allow ceramic tile bending during impact and as such allow tensile stresses to prematurely fracture the plate [8,14,16]. Finally, the adhesive should prevent delamination of the ceramic from the backing plate. If the bonding strength (interface failure) or fracture strain (cohesive failure) of the adhesive is too low, the ballistic impact will potentially result in large areas of ceramic delamination or spalling, even outside of the impact area. Delamination and ceramic spalling dramatically reduces the ability of the armour to perform against multiple ballistic impacts [8,11,12].

The impact of adhesive-layer properties on the ballistic

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performance of multi-layered armour systems has not been extensively investigated in literature, and often the conclusions drawn by different studies can be contradictory. Such contradictory results reported in literature can often be due to the complexity of system failure mechanisms, armour material variation, impact scenario dissimilarity, and critically the complexity of the adhesive material parameter space, where often a variation of a single adhesive parameter is difficult to achieve. Finally, the surface treatment of the front and back plate materials will also have a critical impact on the bonding strength of a given adhesive. As such, if the surface treatment methods vary between studies then the ballistic performance, with comparable adhesives, may also vary.

The objective of this paper is to present an in-depth and systematic literature review into the impact of the adhesive layer properties on ceramic armour ballistic performance. The role of the adhesive properties in ballistic performance will be scrutinised, highlighting trends and disentangling conflicting reports from the literature where possible. Whilst recent interest in reinforced adhesives [22–24] has increased, they will not be included here due to the increased system complexity, making it difficult to identify underlying mechanisms. The article is structured as follows: the reported failure mechanism of a ceramic/metal multi-layered armour system will be explored in the first section, with emphasis placed on the role of the adhesive layer in such failure mechanisms. Adhesive cohesive and adhesion properties of importance will then be discussed in the following section. Each adhesive parameter will be explored in turn and the studies conducted investigating their impact on ballistic performance will be discussed. In the final section the underlying trends and routes for ballistic performance optimisation will be summarised.

2. Ceramic multi-layered armour

Lightweight multi-layer armour systems in their simplest form are comprised of a ceramic front plate and a metallic backing plate. Optimisation of ballistic performance in such simple armour design is often restricted to plate material type and thickness, excluding adhesives [3]. More complex, multi-layered systems [8,25] combining multiple front, intermediate, or back layers are also often envisioned. The use of fibre-reinforced composite intermediate layers, typically para-aramid (e.g., Kevlar® or Twaron®), ultrahigh-molecular-weight polyethylene (e.g., Spectra® or Dyneema®), or liquid-crystal polymer (e.g., Zylon® or Vectran®) materials, is widespread in ballistic armour applications [26,27]. However, investigations isolating the role of the adhesive, via adhesive substitution or thickness variation, on multi-layer armour systems including fibre-reinforced or fabric composite layers are limited [12,15,28,29]. Here it is noted that the studies investigating these composite systems are typically in agreement with the conclusions drawn from other literature studies which use simple ceramic/metal armour systems when probing the role of the adhesive layer. The bonding of additional dissimilar substrates introduces a layer of complexity that results in the role of adhesion on ballistic performance of these complex systems typically not being investigated. Due to these limitations, in describing the underlying ballistic-armour impact interactions the focus in this review article will be on simple armour design and the role of the adhesive layer therein. Nevertheless, the lack of an in-depth analysis on the role of the adhesive layer when bonding ceramics and fibrous polymer composites is highlighted here to the aim of stimulating new research and understanding.

When an armour piercing (AP) round impacts a ceramic/metal armour system, the projectile strikes the front of the ceramic plate, transmitting kinetic energy. A compressive stress wave is generated which propagates through the ceramic generating compressive stresses. When the wave reaches the ceramic/adhesive interface, the mismatch in acoustic impedance results in a partial reflection back through the ceramic plate and a corresponding partial transmission through the adhesive to the backing plate. The reflected wave generates tensile stresses in the ceramic plate potentially causing large amounts of damage due to the ceramic's low tensile strength [5,8].

Meanwhile at the impact point, a Hertzian cone is formed along with radial cracking [4,7,30,31], as shown in Fig. 1(a). The projectile is deformed and eroded by the ceramic plate and the detached cone will continue to erode the projectile. The projectile erosion is of critical importance in ballistic protection performance. If the ceramic plate is not suitably supported, due to use of an adhesive layer with a large thickness and/or low compressive modulus, the ceramic plate will bend, resulting in increased cracking and break-up. Ceramic fragments are also driven radially away from the projectile path, causing shear strains in the adhesive layer. Depending on the shear strength of the adhesive bond, a delamination could be generated. The projectile and detached Hertzian cone will move in the impact direction generating backing plate deformation, as shown in Fig. 1(b).

Depending on the success of the ceramic layer the projectile/fragments will continue to penetrate through the ceramic layer before coming into contact with the adhesive layer and backing plate. Additional deformation or penetration of the backing plate then occurs. Backing plate deformation induces tensile strain in the adhesive layer surrounding the impact zone [11]. This can generate large areas of delamination depending on the adhesion bond strength and cohesive fracture strain. Delaying the ceramic break-up, even by a millisecond [4], can have a dramatic impact on the ballistic performance of the armour due to the additional projectile erosion that occurs. Therefore, even small gains in delaying ceramic front plate failure can have dramatic effects on the ballistic performance.

3. Adhesive bonding layer

The performance of an adhesive material as a bonding agent is dependent on its cohesive and adhesion properties. This performance can be better understood when considering common adhesive failure mechanisms [32] such as those illustrated in Fig. 2.

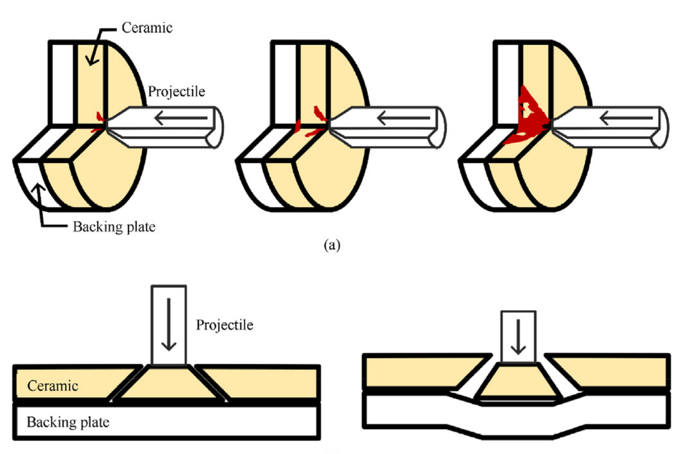

Fig. 1. (a) Formation of a Hertzian cone during ballistic impact of a projectile on a ceramic. The radial and axial crack formation (red) is demonstrated (left to right) as a function of time. Image adapted from Wilkins [4,7]; (b) Once detached, the projectile and cone generate backing plate deformation, whilst the projectile continues to be eroded. Image adapted from Benloulo et al. [30].

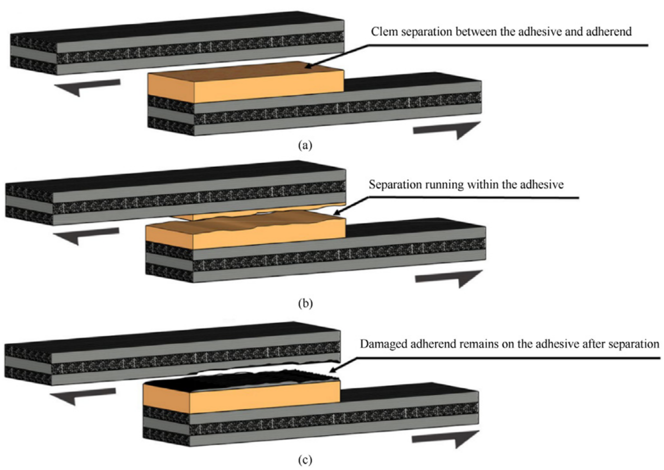

Fig. 2. The three main types of adhesive failure are demonstrated, in the shear configuration. (a) Interface failure; (b) Cohesive failure; (c) Substrate failure. Image adapted from Omairey et al. [32].

Adhesive or interface failure is a failure directly at the interface between the adhesive and the substrate that it is bonded to, illustrated in Fig. 2(a). This type of failure relates to the adhesion properties which are dependent on the adhesive/substrate interaction, surface preparation techniques, and loading type. Cohesive failure, depicted in Fig. 2(b), is a failure in the bulk adhesive, relating directly to the fracture strain (shear or tensile) of the polymeric material. Finally, substrate or adherend failure is when the adhesive bond is stronger than the substrate material itself. The substrate material fails first, leaving material still attached to the adhesive, as illustrated in Fig. 2(c). Substrate failure is not typically observed for ceramic/metal armours.

The adhesion (bond strength) properties contain a complex set of parameters that are highly dependent on the materials involved, surface preparation, and loading type [33]. The bond strength of a joint is typically characterised in three loading scenarios: tensile, shear, and peel. For ceramic multi-layer armour applications the tensile and shear bond strength appear to be of critical importance in preventing interface failure and excessive spalling of the ceramic plate. The bond strength is dependent on the bonding mechanism between the adhesive and the substrate. Bonding mechanisms of important consideration here are mechanical interlocking, physical absorption, and chemisorption. Mechanical interlocking is based on the penetration of an adhesive into micro-pores on the substrate surface, which is adjustable via substrate grit-blasting [34]. Physical absorption is based on intermolecular interactions such as van-der-Waals or hydrogen bonds. Chemisorption is when the adhesive chemically bonds to the substrate, such as covalent or ionic bonding, generating strong levels of bonding. By manipulating surface morphology or chemistry via substrate pre-treatment, the type of bonding and as such the bonding strength can be manipulated [34,35].

When considering the role of an adhesive layer in a multi-layered ceramic armour, the cohesive properties that play an important role are the elastic modulus (stiffness), which provides a stiff coupling between the front and back plate preventing bending and tensional damage, and the fracture strain (ductility), which prevents delamination and reduces ceramic spalling [8].

Finally, an often overlooked adhesive property, which is unrelated to bonding but does affect ballistic performance, is the material's acoustic impedance (Z). The impedance is calculated via the product of material density (ρ) and speed of sound (v) in the material, $Z = \rho v$. Whilst matching the impedance between an adhesive, typically ~2 Mrayl, and a ceramic plate, typically ~45 Mrayl, is incredibly difficult to achieve, even a slight reduction in mismatch is often surprisingly beneficial for the ballistic performance [11,15].

When investigating the mechanical properties of adhesives used in ceramic/metal armours, an important consideration is the high strain-rate observed during ballistic impact [21,25]. Polymeric adhesives have strain-rate dependent mechanical properties and therefore one would expect that the utilisation of high strain-rate dynamic properties is desirable for accurate computational modelling of ballistic scenarios [17]. However, adhesive technical datasheets rarely quote high-strain-rate parameters. The investigation of adhesives under high strain-rate is an ongoing area of research, and often the Cowper-Symonds model [8,10,16,17,20] is utilised in ballistic armour modelling to describe rate-dependent effects. Occasionally, the high-strain-rate parameters are experimentally determined via Split-Hopkinson Pressure Bar (SHPB) experiments [13,16,21,25]. For the purpose of the discussions presented in this literature review and given the difficulties associated with measuring appropriate high strain-rate adhesive properties, the adhesives considered in this paper will be compared based on quasi-static material properties. This allows comparison of ballistic performance based on the adhesive properties. The variation in quasi-static material properties from one adhesive to another are often observed, in the studies discussed here, to be larger than the possible strain-rate variations. This can be seen in the investigation by Shen et al. [8] where the strain-rate dependency was modelled via the Cowper-Symonds model. At quasi-static values the epoxy and polyurethane have elastic moduli of 2500 and 16 MPa, respectively. At a strain-rate of 2000 s^{-1}, using the Cowper-Symonds model and reported adhesive strain-rate parameters, the epoxy and polyurethane have calculated high strain-rate elastic moduli of 3524 and 20 MPa, respectively. The difference in quasi-static and high strain-rate elastic moduli for the two different adhesives are both approximately two orders of magnitude. This indicates that using quasi-static adhesive material properties when correlating ballistic performance with adhesive properties can already provide useful information on the underlying trends.

4. Cohesive properties

Investigations into the impact of adhesive cohesive properties on ballistic performance of ceramic multi-layered armour is typically done via variation in the adhesive chemistry by comparing epoxy- and polyurethane-based materials. Some numerical studies systematically vary the adhesive properties by adjusting the model parameters directly [8]. In this section the impact of critical cohesive properties on ballistic performance will be explored. It is important to note that a variation in one material parameter without affecting others is experimentally challenging. Therefore, the uncertainty in attributing an improved performance to a certain parameter is an important consideration. Not only is parameter isolation a challenge, but interstudy comparisons are often difficult due to variations in armour configurations and ballistic test conditions. Thus, direct quantitative comparison of performance results between studies will not be conducted, but rather a qualitative comparison of conclusions drawn from studies in which a given adhesive parameter was varied.

4.1. Stiffness - Elastic modulus

The elastic modulus, utilising here the tensional value, is often explored experimentally via adhesive substitution. Table S1 summarises the adhesive types, studies, and associated elastic moduli for adhesives used in ballistic impact investigation. The number and variety of adhesives available is extensive and the elastic moduli of such materials can vary by three orders of magnitude. Increasing the elastic modulus of the adhesive layer increases the stiffness of the coupling between the front and backing plate, preventing bending and early ceramic failure.

Shen et al. [8] compared a polyurethane- and an epoxy-based adhesive with elastic moduli of 16 and 2500 MPa, respectively. The single-hit performance, monitored below the ballistic limit, was observed experimentally via residual penetration depth measurement to improve from 3.1 mm to 2.7 mm with increasing elastic modulus, as shown in Figs. 3(a)–3(d). Seifert et al. [9,11] also compared polyurethane- and epoxy-based adhesives, but with a lower variation in elastic modulus, from 4 MPa to 35 MPa. In one study [9] they experimentally observed an improvement in v50-ballistic limit velocity from 911 m/s to 927 m/s for increasing elastic modulus. In their other investigation [11], when considering a threat with a velocity much higher than the ballistic limit, they experimentally observed an increase in backing plate deformation diameter from 63.4 mm to 77.2 mm with increasing adhesive elastic modulus. It is important to note however that they attributed this performance improvement more to the variation in impedance, discussed later in detail. Increasing the backing plate deformation area (radius/diameter) is considered a ballistic performance improvement as the kinetic energy is dissipated over a larger area. Another important observation in this study was that a lower elastic modulus adhesive allowed an increased lateral motion of the impacted ceramic tile, generating undesired additional damage to surrounding ceramic tiles.

Zaera et al. [16] also compared a polyurethane- and an epoxy-based adhesive with elastic moduli of 10 and 2000 MPa, respectively. Experimentally, with a threat velocity greater than the ballistic limit, it was observed that the backing plate deformation area was slightly larger for the epoxy-based adhesive system. This is in direct agreement with Seifert et al. [11] in which the backing plate deformation area increased with increasing adhesive elastic modulus for impact tests above the ballistic limit. Zaera et al. also noted that the overall ceramic damage was qualitatively observed to be less for epoxy bonded tiles. Numerical calculations of the projectile total kinetic energy loss was, when averaged over adhesive and backing plate thickness variations, 1.1% higher for the epoxy-based adhesive indicating again improved ballistic performance with increased elastic modulus (Fig. 3(f)).

Song et al. [15] directly compared a polysulfide adhesive with 2 epoxy-vinyl-ester-based adhesives with elastic moduli of < 10, 2900, and 3300 MPa, respectively. Comparing these adhesives an improvement in v50-ballistic limit velocity was observed (376, 412, and 425 m/s) for increasing adhesive elastic modulus, in agreement with v50-ballistic limit observations by Seifert et al. [9], as can be shown by the experimental residual velocity data shown in Fig. 3(e).

An interesting method of modifying adhesive material properties, including but not limited to elastic modulus, is via the addition of nanoparticles. Gao et al. [13] adjusted the concentration of SiO_2 nanoparticles in E−51 epoxy to investigate the impact on ballistic performance, below the ballistic limit, in a ceramic armour system. From the quasi-static compression stress-strain curve the elastic modulus can be extracted and varies from approximately 850 MPa to 1600 MPa, with increasing nanoparticle content from 0% to 13.3% (by weight). With increasing elastic modulus the backing plate

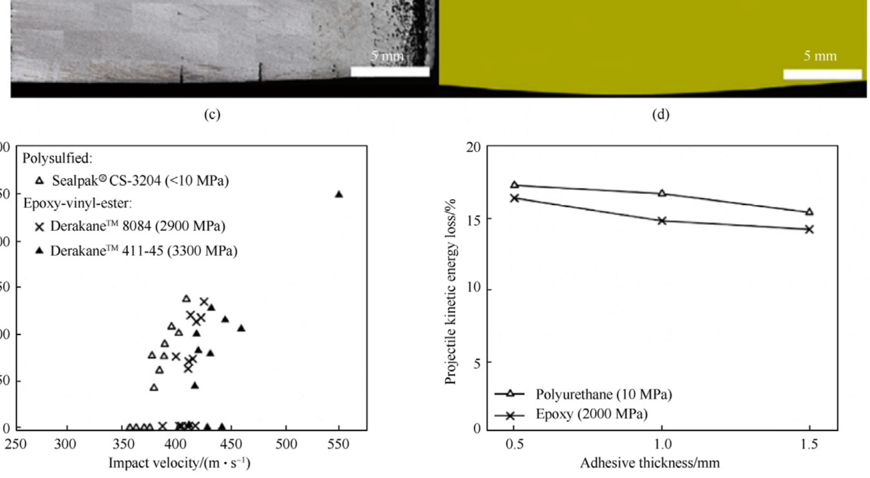

Fig. 3. Residual penetration depth after (a,c) experimental and (b,d) simulated ballistic impact from a 12.7 mm AP round at a velocity of 830 m/s against ceramic multi-layer armour utilising (a,b) an epoxy-based adhesive and (c,d) a polyurethane-based adhesive. Figure reproduced from Shen et al. [8]. (e) The residual velocity as a function of impact velocity for a tungsten carbide ball (12.7 mm diameter) is demonstrated for varying adhesive type in a ceramic/fibre-composite armour system. Data reproduced from Song et al. [15]. (f) Numerically calculated AP tungsten carbide core projectile kinetic energy loss (impact velocity 940 m/s) as a function of adhesive thickness and type for a 4 mm thickness ceramic front plate. Data reproduced from Zaera et al. [16].

deformation height was experimentally found to decrease from 2.80 mm to 2.36 mm, indicating improved single-hit ballistic performance with increasing elastic modulus.

In some studies the specific material properties of the adhesives utilised are unclear and as such conclusions are difficult to state with certainty. However, it can be safely assumed that the elastic modulus of an epoxy-based adhesive will be higher than that of a polyurethane-based adhesive. Buchely et al. [28] investigated the impact of different adhesive types, comparing polyurethane, epoxy, and ethylene-vinyl-acetate/polyethylene blended adhesives against a projectile threat below the ballistic limit. In this study no clear trend in the ceramic damage percentage or projectile stop time as a function of adhesive type was observed, though there was no experimental confirmation of these trends. Übeyli et al. [36] also compared an epoxy- and polyurethane-based adhesive, reporting no clear trend in performance as a function of adhesive type. However, the mechanical properties and thickness of the adhesive layers were not reported.

By increasing the elastic modulus of the adhesive layer the coupling between the ceramic front plate and support backing plate becomes stiffer. Experimentally determined v50-ballistic limit values [11,15] demonstrated that increasing the elastic modulus, via adhesive substitution, improves the ballistic performance. Below the ballistic limit, in which a projectile stop is observed, an increase in adhesive elastic modulus was shown to improve the performance via reduction in residual penetration depth [8] and backing plate deformation height [13]. Above the ballistic limit, when perforation is observed, an increase in ballistic performance was also observed with increasing adhesive elastic modulus. This was observed experimentally via an increase in backing plate deformation area [11,16] and numerically via projectile kinetic energy loss calculations [16].

4.2. Ductility - Fracture strain

The ductility of a material defines its deformability under loading before failure. This can be quantified by the fracture strain. Epoxy-based adhesives are typically brittle (non-ductile) and do not have a plastic deformation region resulting in low fracture strains. Polyurethane-based adhesives are comparatively ductile, with a large plastic deformation region leading to high fracture strains. Here the focus is on the cohesive property of the adhesive, i.e., the fracture strain when cohesive failure occurs, not interfacial failure. When considering the ceramic multi-layered armour system, the ductility has a large impact on the multi-hit ballistic performance. During the impact the adhesive layer is subjected to tensile and shear strains due to the lateral and transverse motion of the ceramic plate with respect to the backing. These strains can be experienced in a large area around the direct impact zone. If the adhesive fracture strain is greater than the plate separation strain (or induced shear strains) it will help prevent ceramic delamination and complete debonding of the tiles (global delamination). Table S1 summarises the fracture strain values for studied adhesives.

The epoxy- and polyurethane-based adhesives compared by Shen et al. [8] had fracture strains of 10% and 400%, respectively. For the epoxy adhesive layer it was experimentally observed, with a threat below the ballistic limit, that approximately 80% of the adhesive area in the sample critically failed (Fig. 4). The polyurethane adhesive, however, only failed locally at the impact point, meaning the system was capable of withstanding a second ballistic impact. In their subsequent simulations the transverse strain induced was monitored as a function of time, Figs. 4(c) and 4(f). At the largest distance from the impact point, 150 mm, the epoxy system still reached a transverse strain of ~100%, far exceeding the fracture strain, thus explaining the large delamination area. The polyurethane system, at 30 mm from the impact zone, reached transverse strains of ~200%, below the polyurethane fracture strain. The polyurethane tensile and shear failure strain properties were then varied in a numerical simulation. Upon increasing the tensile and shear failure strains from 60%–240% and 80%–320%, respectively, a corresponding reduction in ceramic delamination area was observed, from approximately 200 mm^2 to 50 mm^2.

Seifert et al. [11] compared two epoxy and two polyurethane adhesives with fracture strains of 2% and 64% (epoxy adhesives), and 350% and 500% (polyurethane adhesives). In agreement with Shen et al. [8] it was observed that the higher fracture strain polyurethane adhesives were able to withstand impact without critical ceramic delamination, unlike their epoxy counterparts. Interestingly, this observation of reduced delamination with increased fracture strain was experimentally confirmed for above and below the ballistic limit. The induced transverse strain was experimentally monitored from the side of the armour, at the furthest point from impact, using a high-speed camera. Transverse strains observed in the epoxy systems all exceeded fracture strain values, whilst in the polyurethane system the transverse strains were large, approaching 330%, but did not exceed the fracture values.

As previously noted, the adhesive properties in certain studies are unavailable, making conclusions difficult to draw with certainty. Concerning adhesive ductility, it is observed that the fracture strain for an epoxy, as reported in literature, is typically lower than that of a polyurethane comparison. Übeyli et al. [36] compared an epoxy- and a polyurethane-based adhesive layer without disclosing adhesive properties. In agreement with both Shen [8] and Seifert [11] the epoxy systems demonstrated large delamination of the ceramic, whereas the polyurethane system only demonstrated local delamination around the impact zone. This was observed for threats above and below the ballistic limit.

An increase in the adhesive layer cohesive fracture strain allows for higher induced strains, in turn reducing the area of ceramic delamination from the backing plate during impact. This in turn will have a large impact on an armour system's performance against multiple ballistic impacts. Experimental observations of ballistic impacts on multi-layer ceramic armour, above and below the ballistic limit, demonstrated that an increase in adhesive fracture strain resulted in a reduced ceramic delamination area (adhesive failure area) [8,11,36]. Observations of the transverse and shear strain, in experiments [11] and simulations [8], demonstrated that when the induced strains did not exceed the adhesive fracture strain delamination did not occur.

4.3. Acoustic impedance

The mismatch in acoustic impedance between the adhesive layer and the ceramic tile causes a stress wave reflection at the back of the ceramic. This reflected stress wave generates tensile stresses in the ceramic causing additional damage [8] and potentially premature ceramic failure. Alumina ceramic tiles usually have an acoustic impedance of approximately 45 Mrayl [3]. It is important again to emphasise the difficulty of decoupling material parameter effects on ballistic performance. In the current studies, improvements in acoustic impedance matching is often accompanied by an increase in elastic modulus.

Shen et al. [8] numerically monitored the ceramic tile tensile stress evolution for an epoxy- and polyurethane-based adhesive during a projectile impact at a velocity below the ballistic limit. Epoxies generally have a higher acoustic impedance (lower mismatch with the ceramic) compared to polyurethane adhesives, see Table S2, and are as such expected to generate less tensile stress in the ceramic layer. The tensile stress wave diameter and

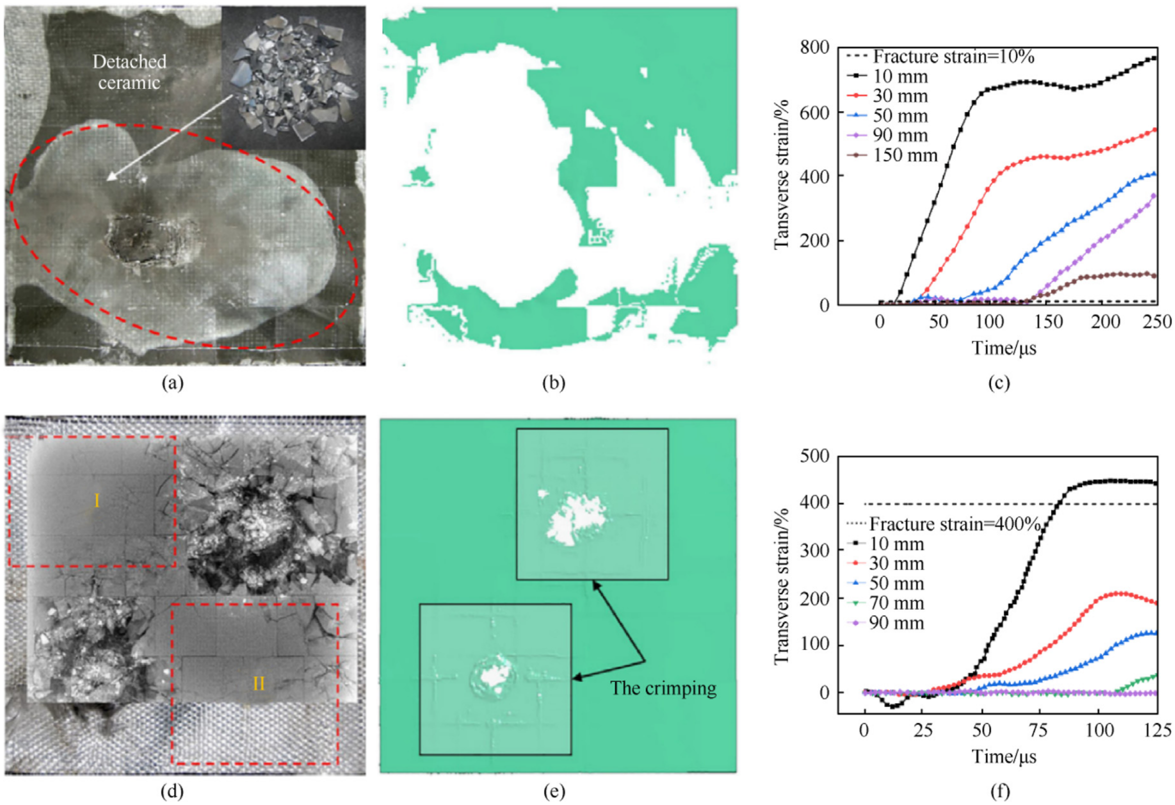

Fig. 4. (a,d) Experimental and (b,e) simulated multi-layer ceramic armour system after ballistic impact. Use of (a,b) an epoxy adhesive demonstrates high delamination and adhesive failure area compared to systems which utilise (d,e) a polyurethane. (c,f) The transverse strain between the ceramic and backing plate is monitored as a function of time and distance from the impact centre. (c) The epoxy system has transverse strains at all distances which far exceed the failure strain of the adhesive. (f) The polyurethane system only exceeds the failure strain local to the impact zone, preventing excessive delamination. Figure reproduced from Shen et al. [8].

magnitude was reduced for epoxy (120 mm & 170 MPa) compared to polyurethane (260 mm & 350 MPa), as shown in Figs. 5(a) and 5(b). The increased impedance mismatch for the polyurethane adhesive system generated additional tensional stress in the ceramic and as such a larger ceramic damage area.

Seifert et al. [9] also investigated epoxy- and polyurethane-based adhesives, with the epoxy-based adhesive demonstrating an improved v50-ballistic limit, attributed to a delayed ceramic plate break up due to a reduction in induced ceramic tensional stress. In an earlier study, Seifert et al. [11] compared a polyurethane and two epoxy-based adhesives in which the acoustic impedance was quoted to be 1.69, 2.8, and 2.31 Mrayl, respectively. The backing plate deformation height, after a perforating impact, was observed to decrease systematically with increasing impedance from 77.2 mm to 63.4 mm, as shown in Fig. 5(c). Gao et al. [13] experimentally varied the acoustic impedance from 0.7 Mrayl to 1.8 Mrayl of an epoxy via the addition of SiO_2 nanoparticles. In agreement with Seifert et al. [11], though here investigated below the ballistic limit, a reduction in the backing plate deformation height was observed (see Fig. 5(d)) with increasing impedance, indicating an improved ballistic performance due to a delayed ceramic breakup.

A direct comparison of polyurethane and epoxy was also made by Zaera et al. [16], with impedance values of 0.1 and 1.6 Mrayl, respectively. The epoxy system demonstrated a qualitatively lower ceramic damage, as well as an increase in backing plate deformation area. The increase in backing deformation area was attributed to a higher transmission coefficient for the compression stress wave. Their numerical study also demonstrated an on average increased projectile kinetic energy loss for epoxy adhesives compared to polyurethane, see Fig. 3(f).

By considering a theoretical comparison of polyurethane and epoxy adhesives, with impedance values of 0.5 and 2 Mrayl, respectively, the importance of a slight increase in impedance can be demonstrated. An increase in impedance of 1.5 Mrayl will reduce the theoretical reflection coefficient from 96% to 83%. A reduction of more than 10% in tensional stress waves will delay ceramic failure and can potentially increase the projectile erosion dramatically. This simple calculation demonstrates the importance of reducing the impedance mismatch, even if a perfect match between an adhesive and a ceramic plate is unachievable.

Increasing the adhesive layer acoustic impedance was shown numerically to reduce the tensional stress induced on the ceramic plate [8]. This reduction in tensional stress, and consequently a delayed ceramic break up, was one of the factors attributed to the improved v50-ballistic limit experimentally observed with increasing adhesive impedance [9]. The single-hit ballistic performance above [11] and below [8,13] the ballistic limit was also experimentally observed to improve with increasing adhesive impedance. It is again important to note that in the studies discussed here an increase in impedance is also accompanied by an increase in elastic moduli and decoupling their effects on ballistic performance is challenging.

Finally, the overall ceramic damage area was also observed experimentally [16] and numerically [8] to reduce with increasing adhesive impedance (both above and below the ballistic limit). The reduction in damage area could potentially allow for an improved multi-hit performance, however the use of epoxy adhesives results in dramatic delamination, due to the reduced ductility discussed previously, removing any potential benefit in multi-hit

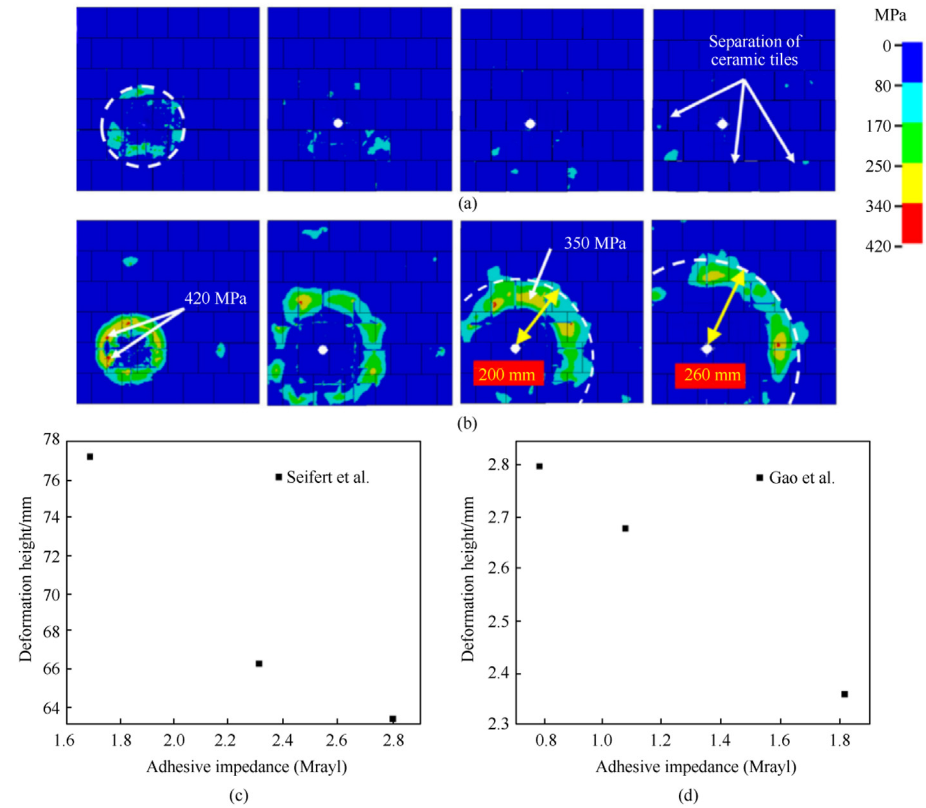

Fig. 5. The evolution of tensional stress waves in the ceramic plate of a multi-armour system with an (a) epoxy and (b) a polyurethane adhesive bonding layer. Epoxy has an increased impedance compared to polyurethane and as such generates reduced magnitude (and reduced area) tensional stress waves from the stress wave reflection at the ceramic/adhesive interface. Figure reproduced from Shen et al. [8]. (c,d) Backing plate deformation height as a function of adhesive bonding layer impedance. Figure reproduced from (c) Seifert et al. [11] and (d) Gao et al. [13].

performance gained via an impedance increase.

4.4. Thickness

The impact of adhesive thickness in ballistic performance is an area of interest for ceramic-based multi-layer armour systems. The work of Wilkins [7] comes as a starting point in understanding the role of adhesive layer thickness in ceramic armour. When studying lightweight ceramic/backing multi-layer armours, although not focusing on the adhesion, Wilkins concluded that, for single-hit ballistic performance, the bond has no structural effect on the target, but rather on the ceramic surface. They showed that to maximise (single-hit) ballistic performance, the adhesive should be thick enough to provide a smooth coupling between the ceramic and the backing. In fact, it was concluded that if careful polishing is applied to both ceramic and backing surfaces, so as to remove surface irregularities, or if lubricant was used to provide a smooth physical coupling between ceramic and backing plate, the ballistic performance equals the performance obtained with the optimal adhesive thickness. This indicates that the role of the adhesive, for single-hit cases, is simply to smooth the physical coupling between the ceramic and the backing. Keeping such results in mind, the studies investigating ballistic performance dependence on adhesive thickness will now be reviewed.

Shen et al. [8] varied the thickness in modelling a polyurethane adhesive layer from 0.2 mm to 3.0 mm, demonstrating that premature ceramic failure occurred with increasing thickness and therefore the projectile kinetic energy loss rate was reduced with increasing thickness. Consequently, it was observed that single-hit ballistic performance, below the ballistic limit, decreased with increasing adhesive layer thickness, though it is important to note that no experimental verification of the thickness dependence was conducted. It was also noted in this study that the radii of adhesive failure (delamination) and radii of ceramic damage decreased with increasing adhesive thickness, as shown in Figs. 6(a) and 6(b). The reduction in ceramic damage radii, from 105 mm to 35 mm, was attributed to an increase in deformation recovery ability and vibrational damping indicating a potential increase in multi-hit performance with increased thickness. Buchely et al. [28] varied the thickness of three different adhesives from 0.1 mm to 1 mm in a numerical model of a projectile impact below the ballistic limit. There was no observed projectile dependence on adhesive thickness and the percentage of damaged ceramic was observed to vary non-monotonically with thickness, with variations of up to 18%. These numerical results were not experimentally confirmed. They also monitored the tensile pressure which relates to the magnitude of the reflected stress wave, and observed an increase in the tensile pressure magnitude in their numerical model with increasing adhesive thickness between 0.1 and 0.4 mm, followed by an approximately constant value for the tensile pressure magnitude. This agrees with Split-Hopkinson pressure bar measurements conducted by Martínez et al. [21], Fig. 6(d). Qualitative observations of the experimental results shows that with increasing adhesive thickness a reduction in delamination and surrounding tile damage was observed, which is in agreement with Shen et al. [8].

The shear strain capacity was observed to increase with increasing adhesive thickness by López-Puente et al. [14], with epoxy thickness varying from 0.1 mm to 1.1 mm. For impacts equal to or less than the ballistic limit this resulted in the experimentally observed ceramic tile delamination reduction, in agreement with

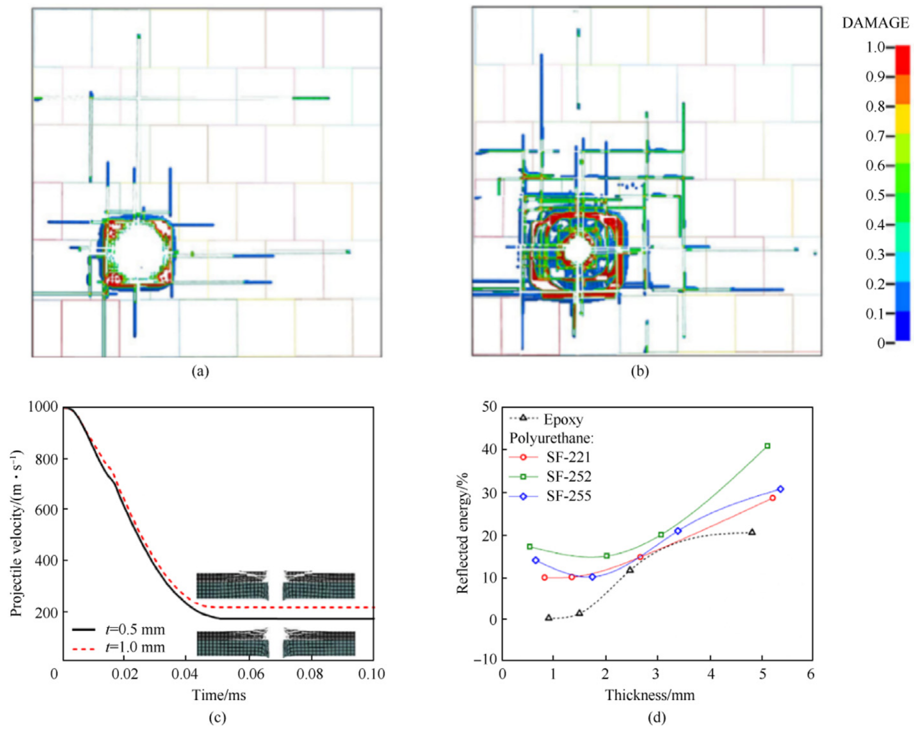

Fig. 6. The interior ceramic damage at 300 μs for (a) 3.0 mm and (b) 0.5 mm adhesive layer thickness. Reproduced from Shen et al. [8]. (c) The projectile velocity as a function of time, with an increased residual velocity for an increased adhesive thickness. Reproduced from Arslan et al. [19]. (d) The reflected energy as a function of adhesive thickness and type as measured via split Hopkinson pressure bar. Reproduced from Martínez et al. [21].

Shen et al. [8] and Buchely et al. [28], and as such should result in better multi-hit performance. The single-hit ballistic performance was observed to vary non-monotonically with adhesive thickness due to two competing mechanisms. With increasing thickness an increase in ceramic damage and fragmentation was observed numerically, attributed to an increased ability for the ceramic tile to bend and fracture. This contrasts directly with the results from Shen et al. [8]. Simultaneously there was an observed increase in backing plate deformation area with increasing thickness (observed experimentally and numerically), indicating an improved energy distribution. These competing effects are realised when observing the numerically calculated remaining armour thickness as a function of adhesive thickness. In both armour configurations studied an optimal thickness of ~0.3 mm was identified, balancing the trade-off in premature ceramic failure/ceramic damage and improved energy distribution.

Zaera et al. [16] varied the thickness of a polyurethane- and an epoxy-based adhesive in a ceramic multi-armour system, experimentally observing, in agreement with López-Puente et al. [14] though for impacts above the ballistic limit, that the increased thickness generated increased ceramic bending and fracturing. It was also observed, again in agreement with López-Puente et al. [14], that an increase in adhesive thickness resulted in an increased backing plate deformation area, both numerically and experimentally. Numerical calculations of the projectile kinetic energy loss as a function of adhesive thickness were conducted and for all adhesive types/armour configurations a reduction in kinetic energy loss is observed, see Fig. 3(f), with increasing adhesive thickness, in agreement with Shen et al. [8]. This indicates that the premature ceramic failure, from increased bending, is the critical process in determining ballistic performance.

Pisavadia et al. [17] numerically modelled an alumina/metal armour system with varying epoxy adhesive layer thickness, observing an increased projectile stop time, from 57 μs to 60 μs, and an increased penetration depth, from 6 mm to 7.5 mm, with increasing thickness for an impact below the ballistic limit. Both results indicate a reduction in single-hit ballistic performance for increasing adhesive thickness, in agreement with Zaera [16], López-Puente [14], and Shen [8]. It was also observed that the ceramic damage area decreases with increasing thickness, in agreement with Shen et al. [8]. A 26% increase in projectile residual velocity with increasing adhesive layer thickness was numerically observed by Arslan et al. [19], as shown in Fig. 6(c), for a perforating impact. Here, an increase in shear capacity, with increasing adhesive thickness, was also confirmed by the lack of adhesive shear cracks in the thicker layers. An increase in shear capacity with increasing thickness was also demonstrated in numerical modelling by Prakash et al. [20]. In this study the backing plate deformation area was also found to increase with increasing adhesive thickness, in agreement with observations from López-Puente [14] and Zaera [16]. There was, however, no clear relationship between residual penetration depth and adhesive thickness, similar to observations by Buchely et al. [28].

Gao et al. [10] also experimentally observed no projectile kinetic energy dependence on adhesive thickness. A decrease in ceramic damage area and an increase in backing plate deformation area was observed with increasing adhesive thickness. Interestingly, in contrast with many other studies, a single-hit ballistic performance improvement was observed with increasing adhesive layer thickness. The backing plate penetration depth was observed to decrease from 27.2 mm to 24.5 mm with increasing adhesive thickness layer. This was potentially attributed to an increase in the shear capacity of the adhesive layer with increasing thickness. It is noted that this study concerns a much higher velocity impact, 1900 m/s, of a tungsten alloy ball projectile, compared to other studies which typically utilise AP rounds at velocities of 800 m/s. This difference could potentially explain the conflicting report of improved single-hit ballistic performance with increasing adhesive thickness.

In this section it is clearly demonstrated how complex and occasionally contradictory the conclusions drawn from ballistic performance dependence on adhesive thickness can be. This is a result of the multi-faceted mechanisms that occur and the difficulty in directly comparing multiple studies. Giving emphasis on studies with experimental verification the following conclusions on the impact of adhesive thickness on ceramic multi-layer armour can be drawn. It appears that increasing the adhesive thickness layer reduces the single-hit ballistic performance, with projectile kinetic energy calculations from modelling demonstrating reduced energy loss above and below the ballistic limit [8,16,17,19]. Increasing the adhesive thickness increases the magnitude of the tensile stress generated on the ceramic tile via stress wave reflections, as observed in models [28] and experimental [21] investigations. This can lead to premature ceramic breakup and result in the observed reduction in single-hit ballistic performance. Conversely an increase in adhesive layer thickness is observed in experimental [14,16] and numerical [14,16,20] studies, above and below the ballistic limit, to increase the backing plate deformation area indicating an improved performance. It would appear that there are two competing mechanisms that improve or reduce the single-hit ballistic performance when increasing adhesive thickness, therefore indicating an optimal thickness for a given system.

Increasing adhesive thickness increases the shear strain capacity of the layer [8,14,19,28] resulting in a reduced ceramic tile delamination area under impacts above [19] and below [8,14,28] the ballistic limit, as such improving the multi-hit ballistic performance. However, there is potentially a simultaneous increase in ceramic damage area [14,16] due to the increased ability for the ceramic tile to bend under impact and the increased tensile stress generation. An increase in ceramic damage area was experimentally observed at above the ballistic limit [16], whilst studies below the ballistic limit demonstrate no clear consensus in ceramic damage area dependence on adhesive thickness, with conflicting reports from experimental [10] and modelling [8,14,17] studies. Therefore, it appears again that there is an optimal thickness when considering the multi-impact performance dependence on adhesive thickness and as such an optimal thickness depending on the armour system specifications.

5. Adhesion properties

The adhesive adhesion (bond strength) properties are dependent on the adhesive and substrate chemistry, the loading type, and surface preparation. When considering adhesive properties the two of most interest are the tensile and shear strength of the bond. If the tensile or shear strength are exceeded during impact it will result in adhesive interface failure. The substrates must be appropriately prepared, cleaned, and degreased to ensure optimal bond performance. Contaminants present at the bond interface can result in a bonding strength reduction. An increase in bonding strength is expected to reduce ceramic delamination and thus improve multi-hit ballistic performance. Adhesive strength variation via adhesive substitution is often conducted, but it is typically very difficult to then decouple the additional material parameter variations such as fracture strain. Therefore, in this section a focus is given to investigations which utilise surface modification as a technique of controlling adhesive bond strength and numerical investigations which are able to vary this input parameter directly.

Shen et al. [8] experimentally measured the tensile and shear strength of epoxy and polyurethane adhesives to steel with butt-joint and singly-lap-joint tensile testing. The tensile and shear bond strength for the epoxy and polyurethane were (27, 17) MPa and (10, 8) MPa, respectively. The tensile bond strength in both cases is observed to be higher than the shear bond strength. Experimentally the epoxy demonstrated increased delamination, but this is attributed to the dramatic reduction in fracture strain, discussed earlier in detail, rather than any effect of bond strength. However, in their numerical investigation the bonding strength was directly varied for the polyurethane adhesive. By increasing the tensile bond strength from 10 MPa to 50 MPa, and the shear bond strength from 8 MPa to 40 MPa, a reduction in delamination area of approximately 50 mm^2 was observed.

A novel bonding strength modification method was investigated by Jang et al. [37], in which nanostructured surface modifications were employed. ZnO nanowires and anodized aluminium oxide nanoholes were fabricated on the surfaces, as demonstrated in Figs. 7(b) and 7(c). An epoxy-adhesive was then utilised and depending on the combination of surfaces the adhesive strength varied. It is important to note that the samples were subject to low-velocity drop tower impacts, with no perforations observed. The backing plate deflection height reduced with increasing adhesive bonding strength (due to the surface treatment) indicating an improved armour performance, Fig. 7(a). It is hypothesised that a reduced adhesive failure area increases the ability for a cohesive response from the armour system and thereby improving the performance.

Harris et al. have extensively investigated the use of ceramic surface treatment as a method for adhesive bond strength improvements [12,34,35]. An investigation into the effect of refiring and laser treatment of silicon carbide was conducted [35]. The non-surface modified control had a tensile and shear bond strength of 11 and 6 MPa, respectively. Refiring the silicon carbide tile in air at 1100 °C for 1.5 hr increased the tensile and shear bond strength to 13 and 31 MPa, respectively. Laser ablation, using a 248 nm krypton fluoride ultra violet excimer laser, of the silicon carbide increased the tensile and shear bond strength further to 23 and 28 MPa, respectively. The effect of surface treatment on alumina has also been investigated [34]. Laser ablation, as utilised also for silicon carbide, was used as a method for surface treatment with varying laser settings. The non-treated alumina control had a tensile and shear bond strength of 31 and 30 MPa, respectively. Shear and tensile bond strength increased to 36 and 32 MPa, respectively, with laser ablation settings of 50% power and 50% overlap. It is noted that the failure mode for this sample in tension was cohesive and not interfacial. For laser ablation settings of 100% power and 0% overlap, the tensile bond strength increased to 33 MPa, whilst the shear bond strength reduced to 28.6 MPa. An overview of the bond strength versus surface treatment can be seen in Fig. 7(d). Harris et al. [12] then utilised these surface treatment methods to experimentally investigate the effect on ballistic performance with velocities approximately equal to the ballistic limit. Firstly, the failure mode was observed to change with increasing adhesive bond strength. The laser-treated silicon carbide was found to have failed via cohesive failure, rather than interfacial fail observed in the refired and control samples. Secondly, the total damage observed for the laser-treated armour systems was reportedly lower, with the laser-treated panel being the only panel which could prevent penetration of all 4 ballistic impacts, as observed in Figs. 7(e) and 7(f).

A numerical investigation was also conducted by Yao et al. [18] in which the tension and shear failure force (bond strength) was varied. With increasing bond strength a reduction in the depth of penetration was observed.

Increasing the adhesive tensional or shear bond strength was shown via modelling to reduce the delamination area during ballistic impact [8]. This reduction in interfacial adhesive failure is attributed to the improved multi-hit ballistic performance

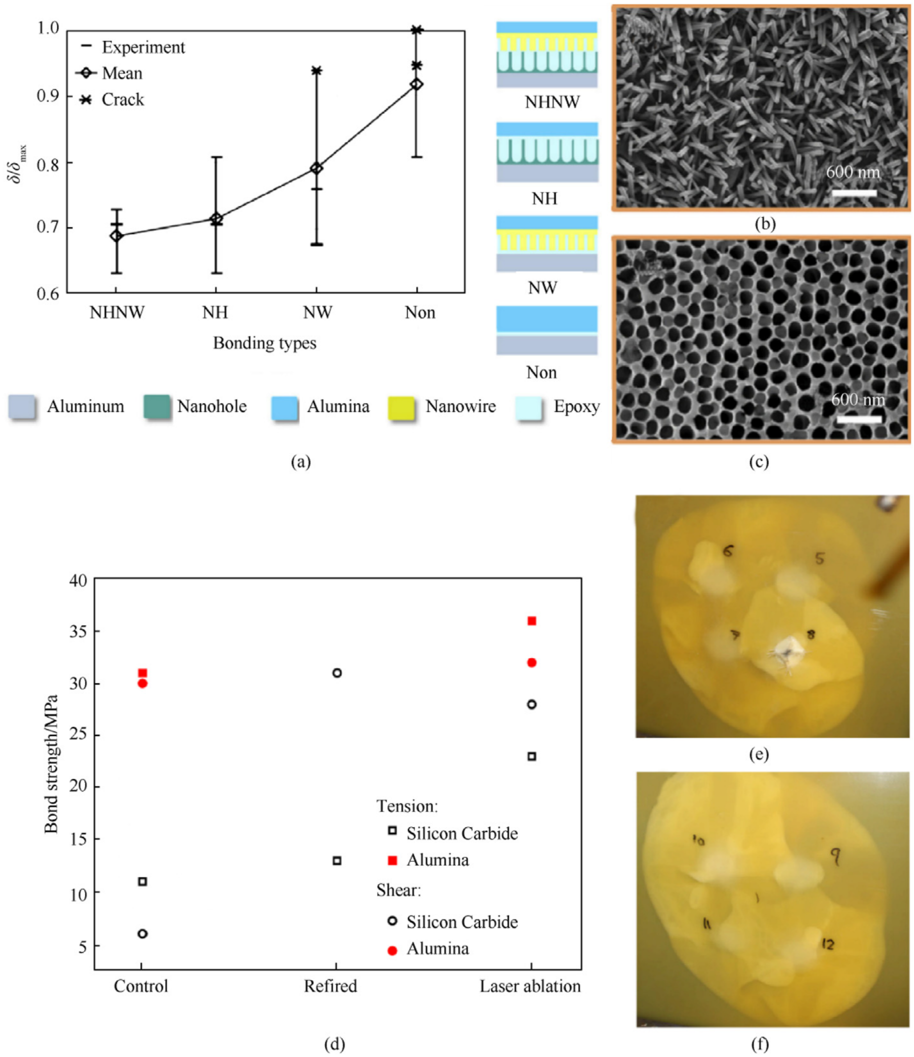

Fig. 7. (a) The backing plate deflection after low-velocity impact for varying surface treated ceramic/metal armour systems. Surface treatment includes various combinations of (b) nanowires and/or (c) nanoholes. Image reproduced from Jang et al. [37]. (d) The tensile (square symbols) and shear (circle symbols) bonding strength per surface treatment technique for silicon carbide (black) and alumina (red). The ballistic tests for a multi-layer armour system with (e) refired silicon carbide and (f) laser ablation treated silicon carbide. An improved ballistic performance with higher bond strength is observed. Image reproduced from Harris et al. [12,34,35].

observed experimentally at approximately the ballistic limit [12]. Interestingly, it appears that an increase in bonding strength also improves the single-hit performance of the ceramic multi-layer armour, though ballistic experimental verification is required. It was observed experimentally, at low velocity, that the backing deformation height decreased with increased bonding strength, whilst numerical modelling demonstrated a reduced depth of penetration with increased bonding strength [18].

6. Other parameters

Other material parameters occasionally discussed as important factors for an armours ballistic performance will be discussed here.

Seifert et al. [11] discussed the impact of adhesive viscosity on the surrounding tile damage outside of the impact area. It was noted that the lower viscosity adhesive was able to infiltrate the inter-tile gaps and provide additional support to the ceramic tiles, damping lateral motions, and preventing additional crack propagation across tile boundaries.

The impact of poor adhesive application method was explored numerically by Pisavadia et al. [17] in which the impact of defects (trapped air) in the adhesive layer of an armour system was explored. With increasing defect concentration from 0.5% to 7.5% a corresponding increase of 0.14 μs in projectile stop time was observed. The penetration depth also increased from 15.4 mm to 15.5 mm, demonstrating the importance of manufacturing quality.

7. Discussion

The adhesive cohesive properties which influence ballistic performance in ceramic multi-layer armours can be summarised from literature as the adhesive elastic modulus, fracture strain, and acoustic impedance. Meanwhile, the bonding adhesion properties observed to affect ballistic performance are tensional and shear bond strength. The adhesive thickness is shown to also play a critical role in determining ballistic performance.

Increasing elastic modulus of an adhesive layer increases the stiffness of the coupling between the ceramic strike plate and backing support plate. The elastic modulus is typically studied via adhesive substitution, often comparing high elastic modulus epoxy with low elastic modulus polyurethane. An increase in elastic modulus was observed across a number of studies to improve the single-hit ballistic performance. Better ballistic performance in the form of residual penetration depth reduction [8], v50-ballistic limit increase [11,15], projectile kinetic energy loss increase [16], and backing plate deformation height reduction [13] was observed with increasing adhesive elastic modulus.

Note, however, that an increase in elastic modulus is typically accompanied, when substituting adhesive type, by a reduction in the fracture strain. During ballistic impact the ceramic tile experiences transverse and lateral motion relative to the backing plate, inducing strains in the adhesive layer. If the transverse or lateral strain experienced by the adhesive exceeds the fracture strain, cohesive failure will occur resulting in delamination. An increase in fracture strain was observed across a number of studies to reduce the amount of delamination and as such improve the multi-hit performance. Improvements in multi-hit performance are measured via reduced delamination area [8,11,36] and are attributed to directly observed transverse strains not exceeding the adhesive fracture strain [8,11].

This review makes clear that an ideal adhesive for optimisation of both single- and multi-hit ballistic performance should have both high stiffness and large fracture strain. However, such adhesive materials have not yet been synthesised for multi-layer armour systems. Instead, adhesives commonly utilised, such as epoxy or polyurethane, are either stiff and brittle or soft and ductile. Adhesives with high elastic modulus provide better support to the ceramic tile, improving single-hit performance. However, because such adhesives with high elastic modulus often have low fracture strain, the ceramic tiles will often globally delaminate [8,11,36] from the backing plate when hit by a projectile. With global delamination the armour system is no longer able to provide any protection against ballistic threats. Conversely, adhesives with low elastic modulus and high fracture strain show reduced single-hit performance, but better multi-hit capabilities, highlighting the trade-off that the armour designer needs to consider.

The importance of impedance matching between the ceramic and adhesive layer to reduce the reflection magnitude of the stress wave at the interface and improve ballistic performance was clearly demonstrated [8,9,11,13,16]. Reducing the produced tensional stress waves during ballistic impact is of critical importance to prevent premature ceramic failure and increase the amount of projectile erosion. A better impedance match also increases the transmission coefficient of the stress wave, increasing wave transmission to the backing plate. Reducing the mismatch in impedance was indicated to improve v50-ballistic limit measurements [11], reduce ceramic damage area [8,16], reduce backing plate deformation height [9,13], and increase backing plate deformation area [16]. Once more, note that an increase in acoustic impedance (decreasing the mismatch with the ceramic strike face) is accompanied by an increased adhesive elastic modulus, inherently providing better single-hit performance though typically at the cost of larger delamination areas (due to low fracture strain) and thus a worse multi-hit performance. A review of the available literature shows that it is difficult to differentiate which positive effects on ballistic performance are due to a higher acoustic impedance of the adhesive and which are due to the increased adhesive elastic modulus.

Increasing the thickness of an adhesive bonding layer reduces the support stiffness provided to the ceramic front plate potentially inducing early ceramic failure and reducing single-hit ballistic performance. There is simultaneously an increase in strain capacity and vibrational damping with increasing adhesive layer thickness, which reduces the ceramic delamination and damage areas. With increasing thickness there is also an observed increase in the magnitude of the reflected stress wave before plateauing at approximately 0.4 mm, increasing the ceramic tensile damage and potentially inducing premature ceramic failure. However, increasing the thickness seems to positively influence the multi-hit ballistic performance up to a certain threshold with observed decrease in delamination area [8,14,28], decrease in ceramic damage area [8,10,17], and increase in backing plate deformation area [10,14,16,20]. Simultaneous negative trends for single-hit performance were observed with increase in tensile stress waves [21,28], reduced projectile kinetic energy loss [8,16,17,19], and increase in residual penetration depth [17], which is in line with the seminal work of Wilkins [7]. Wilkins showed that, for single-hit performance, the adhesive bonding layer should be just thick enough to provide a smooth contact coupling between the ceramic and the backing. Thus, variations in adhesive thickness results in, yet again, competing mechanisms with regards to ballistic performance for single- and multi-hit. In practical cases there is often an optimal unique thickness for a given adhesive-armour combination which can balance the trade-offs between single- and multi-hit performance.

Increasing the adhesive tensional or shear bond strength prevents interface failure and reduces the area of delaminated ceramic tile. The ability to directly manipulate the bond strength through surface treatment methods was clearly demonstrated [12,34,35,37] and a reduction in backing plate deformation heigh [37] and improved multi-hit performance [12] was observed with increasing bonding strength.

Finally, this discussion must point out that the studies addressing the role of adhesive bonding layers in ballistic performance of ceramic multi-layer targets consider only metal or fabric composite backings. However, composite materials, more specifically Fibre Reinforced Polymers (FRP) are logical substitutes to heavy steel armour plates for future lightweight armoured vehicles. Composites present many advantages to be employed in armoured vehicles such as corrosion resistance, scalability of multifunctional capabilities, and significant weight reduction [38].

8. Conclusions

In the design and optimisation of the adhesive layer in a ceramic-based multi-layer armour system there is often a trade-off between single- and multi-hit ballistic performance. The literature reviewed in the present paper measured improved single-hit performance by means of residual penetration depth reduction, v50-ballistic limit increase, projectile kinetic energy loss increase, backing plate deformation height reduction, increased backing plate deformation area, and a reduced ceramic damaged area. Improved multi-hit performance has been measured in terms of reduced delamination area, reduced ceramic damage area, and improved number of projectile stops.

Particularly, the thorough review of the literature presented herein indicates that improvements in the single-hit ballistic performance can be achieved via maximised elastic modulus accompanied by maximised impedance value. This is typically at the cost of worse ballistic performance in multi-hit conditions due to commercially available high elastic modulus adhesives, such as epoxies, having low fracture strains. Meanwhile, improvements in multi-hit ballistic performance can be achieved via a maximised fracture strain, often at the cost of worse single-hit performance, which is commonly the case in commercially available polyurethane-based adhesives which have a low elastic modulus.

Maximising adhesive bond strength via optimal surface treatment is shown to provide improved single- and multi-hit ballistic performance, while adhesive bonding layer thickness must be optimised for the specific ceramic/adhesive/backing combinations. If the adhesive layer is too thin, the delamination area is larger and failure of the ceramic seems to occur earlier due to non-smooth coupling of the ceramic strike-face with the backing plate. If the adhesive is too thick, ceramic support is reduced and the magnitude of the reflected stress wave is higher, yielding premature ceramic failure.

The present review also indicates paths to be followed in future research. The synthesis of adhesives maximising both elastic modulus and fracture strain, the measurement and modelling of ballistic performance of delaminated and broken ceramic tiles, and both empirical and physics-based determination of the design envelope provided by different adhesives are important topics for future research. In addition to that, investigations into the effects of bonding parameters variation on the ballistic performance of lightweight ceramic/composite armours is incredibly limited. Research focusing on the optimisation of the adhesive layer between ceramic and lightweight composites is of critical importance for the future of lightweight armour solutions and should be addressed in future investigations.

CRediT authorship contribution statement

Ethan I.L. Jull: Writing – review & editing, Writing – original draft, Conceptualization. **Richard Dekker:** Writing – review & editing, Conceptualization. **Lucas Amaral:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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