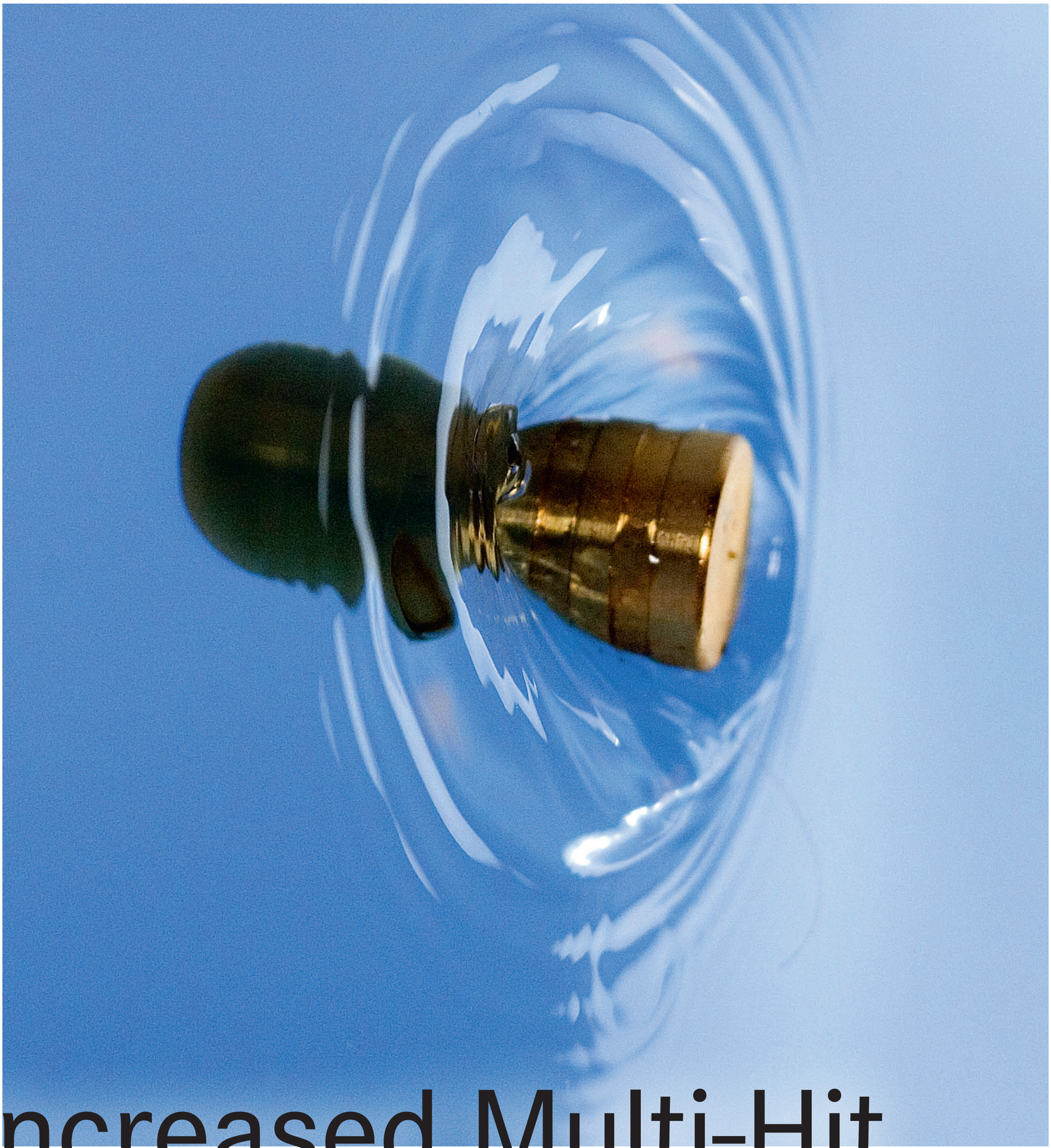

Increased Multi-Hit Performance

of Ballistic Armour by Shockwave Damping Adhesives

Content

1 Contact

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2 Modern Vehicle Protection

Military and security forces constantly must adapt to new challenges to ensure the protection of the population. Whether in alliance defence or in the international fight against aggressors and terrorism, our armed forces are confronted with ever-increasing threats. Armoured vehicles, whether on land, air or sea, form part of the tactical infrastructure of civilian and reliable units. In addition to IEDs and EFPs, these vehicles must also offer protection against heavy ballistic calibres. A particular challenge is to achieve the necessary level of protection with the lowest possible weight. Therefore, high-performance materials are used in modern ballistic composite systems (Figure 1), which guarantee maximum protection even in the event of direct fire and mine explosions.

Ceramic composite systems offer maximum protection in vehicle protection with a significantly lower surface weight than conventional steel solutions. The structure in a multi-tile network ensures that the system can withstand multiple attacks, e. g. under machine gun fire.

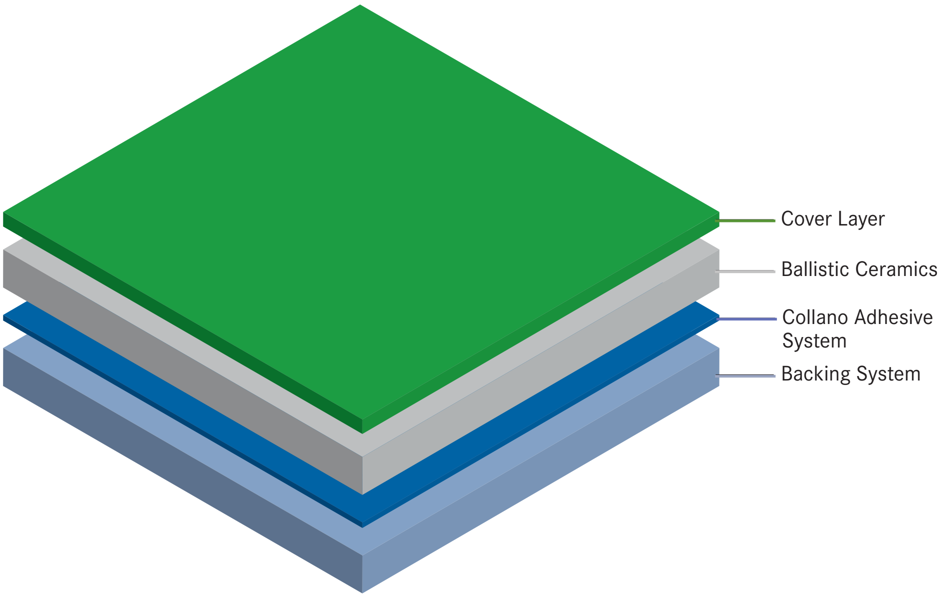

Figure 1: Schematic structure of a ballistic composite system.

In addition to ensuring multi-hit resistance through the structural design, the choice of material plays a crucial role. Each fulfils a specific function. The hard ceramic layer slows down the projectile and leads to its fragmentation. The backing can now fully absorb the residual energy and fragments.

The adhesion between the ceramics and the other composite substrates plays a key role in the performance of the entire system because the system adhesive does not just have the task of connecting the individual materials with one another. On the one hand, it forms the boundary layer between the individual ceramic components and prevents cracks that spread from the point of entry from propagating into the surrounding ceramics. This effect increases with increasing elasticity of the adhesive. On the other hand, a suitable adhesive can also contain the shock wave propagation in the overall structure, thus preventing lateral delamination and minimizing the damage radius around the bullet point. As a result, the right adhesive can significantly increase the multi-hit resistance of ceramic composite armour and make a significant contribution to protecting life and limb.

3 Ballistic Effects in Ceramic Composite Armour

When the armour-piercing projectile hits the surface of the system, part of the energy is already captured by the dwell effect without penetrating the system (Figure 2). As a result of the high energy and shock cell propagation, however, the ceramic is destroyed by microcracks. Further energy is then dissipated by erosion of the projectile fragments as they penetrate the conoid ceramic layer. The backing, consisting of high-performance fibres in a polymer matrix, can then absorb both the fragments and the residual energy in the direction of fire.

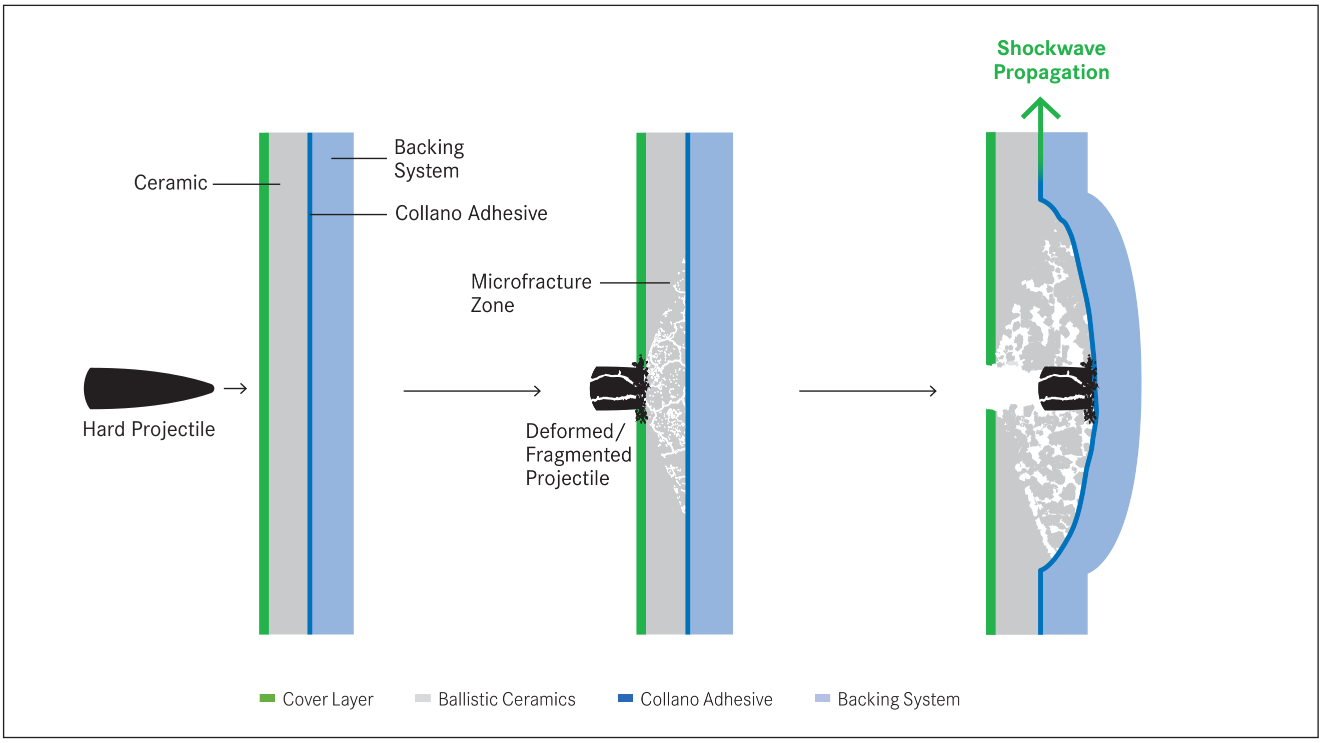

Figure 2: Dissipation of energy from projectile impact.

In addition to these effects in the direction of fire, there is also plastic deformation and shock wave propagation in the lateral plane. This is decisive for the extent of the impressive radius of the entire system around the point of entry, but also for the propagation of lateral delamination of the composite structure. While the direct impact of the individual ceramics is contained by the multi-tile composite structure, surface delamination can also reduce the functionality of the system beyond the ceramic components or even lead to the complete loss of the performance of the protection system. The range of the increase is a direct measure of the resistance to multiple hits.

4 Shockwave Transmission and Cause of Delamination

When a bullet hits the strike face of an armour system waves are propagating through the whole system. Beside the damage area surrounding the point of impact surface waves are continuing propagation in lateral directions, like the behaviour of water when a stone is thrown in (Figure 3).

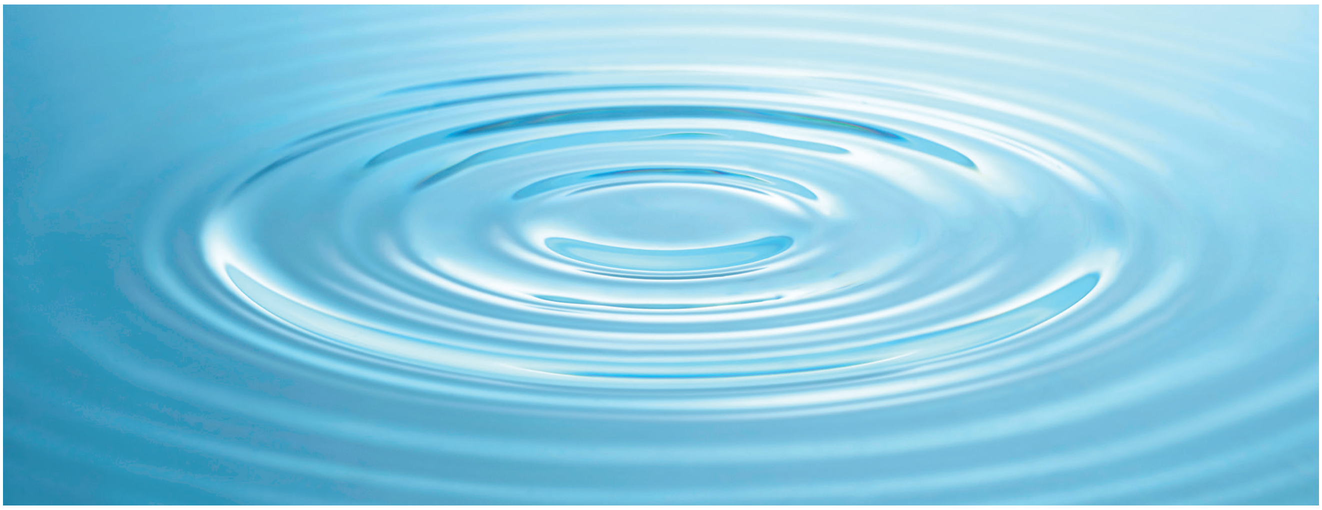

Figure 3: Wave propagation on a water surface after stone impact.

In a composite system these waves cause lateral delamination when their force is higher than the bonding strength between the composite materials (Figure 4).

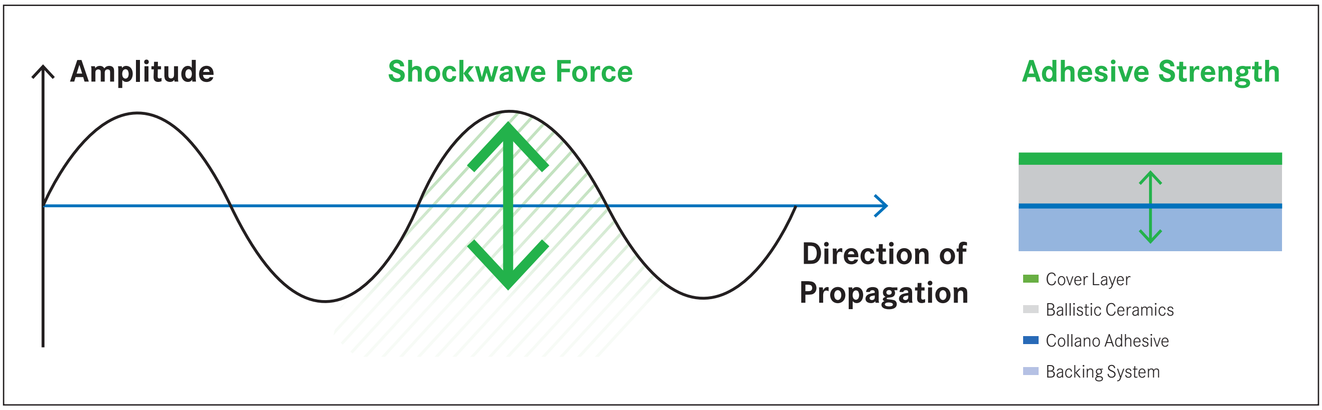

Figure 4: Shock wave propagation in lateral direction.

The transmission range, intensity and speed depend on the material the waves are passing. In an undamped system the sound velocity of the material is significant for the propagation of the wave. It generally depends on the density ρ, the young's modulus E and the poisson constant ·v. For transverse waves, with oscillation direction vertical to their direction of propagation it is valid:

$$c_{solid,\ transverse} = \sqrt{\frac{E}{2\rho\ (1+\nu)}} = \sqrt{\frac{G}{\rho}} \quad \rightarrow \text{ with G as shear modulus.}$$

Already here it becomes clear that the elasticity of the system has a significant influence on the wave propagation.

5 Transmission Influence of the Adhesive

Viscoelastic systems are a special case among solids. In vibrational rheometry, their behavior under oscillating shear stress is described by the complex shear modulus G*. This consists of the storage modulus G', which describes the elastic part and thus the stiffness, and the loss modulus G'', which describes the viscous part and represents a measure of the damping.

$$G^* = G' + i \cdot G''$$

The vibration-damping property of the system is enhanced by the loss modulus and inhibited by the storage modulus. This behavior can be easily explained by imagining a vibration transmitter connected to a vibration sensor (Figure 5). When connected with a rope (high loss modulus) nearly no effect arrives at the vibration sensor, while with a rod connection (high storage modulus) the energy is transferred to the vibration sensor.

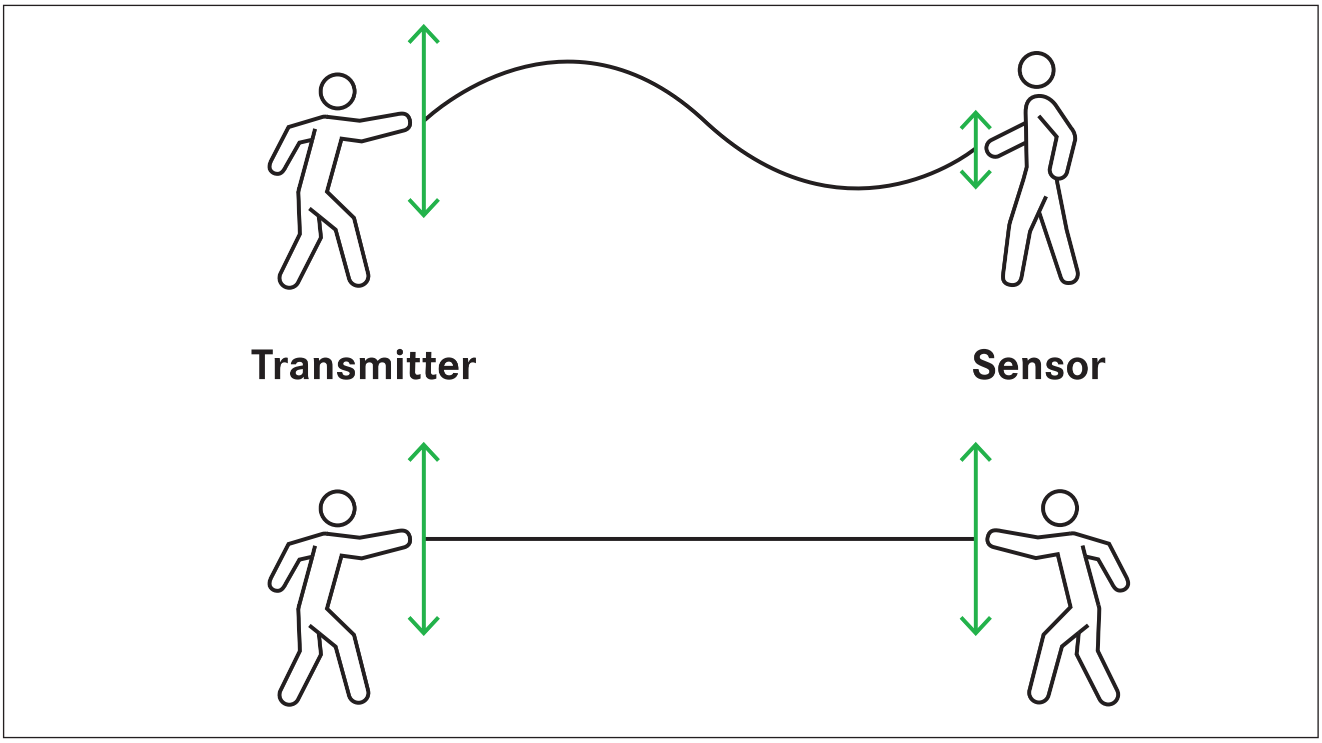

Figure 5: Vibration transmission with flexible (above) and rigid (below) connection.

The dissipation factor tan δ is defined as the ratio of loss modulus G'' to storage modulus G'.

$$\tan \delta = \frac{G''}{G'}$$

Therefore the dissipation factor tan δ describes the damping behaviour of visco-elastic materials and it directly correlates with the logarithmic decrement Λ, with the amplitude A and the way s:

$$\tan\delta = \frac{\Lambda}{\pi} = \frac{1}{\pi}\ln\frac{A_{max}(s)}{A_{max}(s+1)}$$

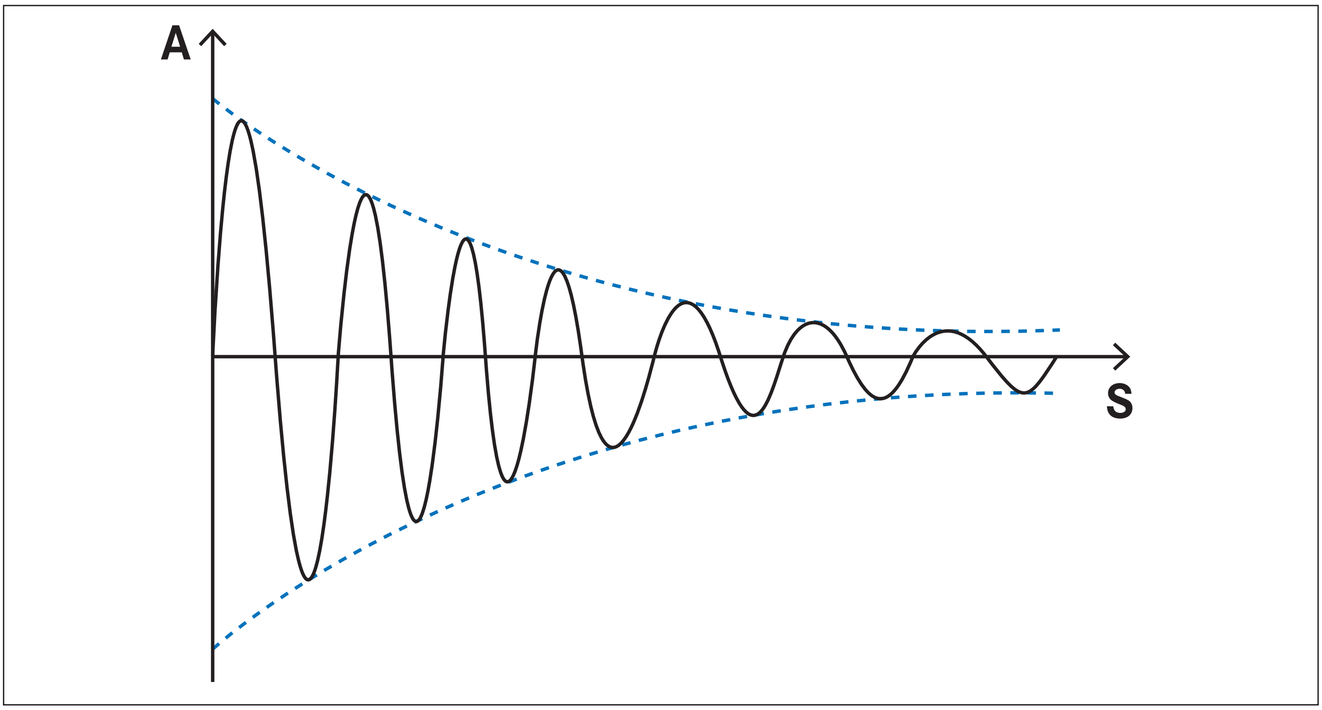

Figure 6: Weakening of the amplitude A over the path s.

This connection shows that the strength of the shockwave as well as its range depends on the damping behaviour of the adhesive, desciribed by the dissipation factor tan δ. This tan δ directly correlates with the absorbed energy. The higher the damping performance of the adhesive, the lower the energies and ranges of the transversal shockwaves propagating in the plain. Therefore a high damping performance of the adhesive is able to avoid lateral delaminations and minimizes the damage range around the strike point.

6 Influences on the Damping Performance

The dissipation factor, as value for the damping performance, itself is frequency and temperature dependent. The frequency dependence can be converted into characteristic strain rates, which are between $10^3 s^{-1}$ and $10^6 s^{-1}$ for ballistic applications (Figure 7).

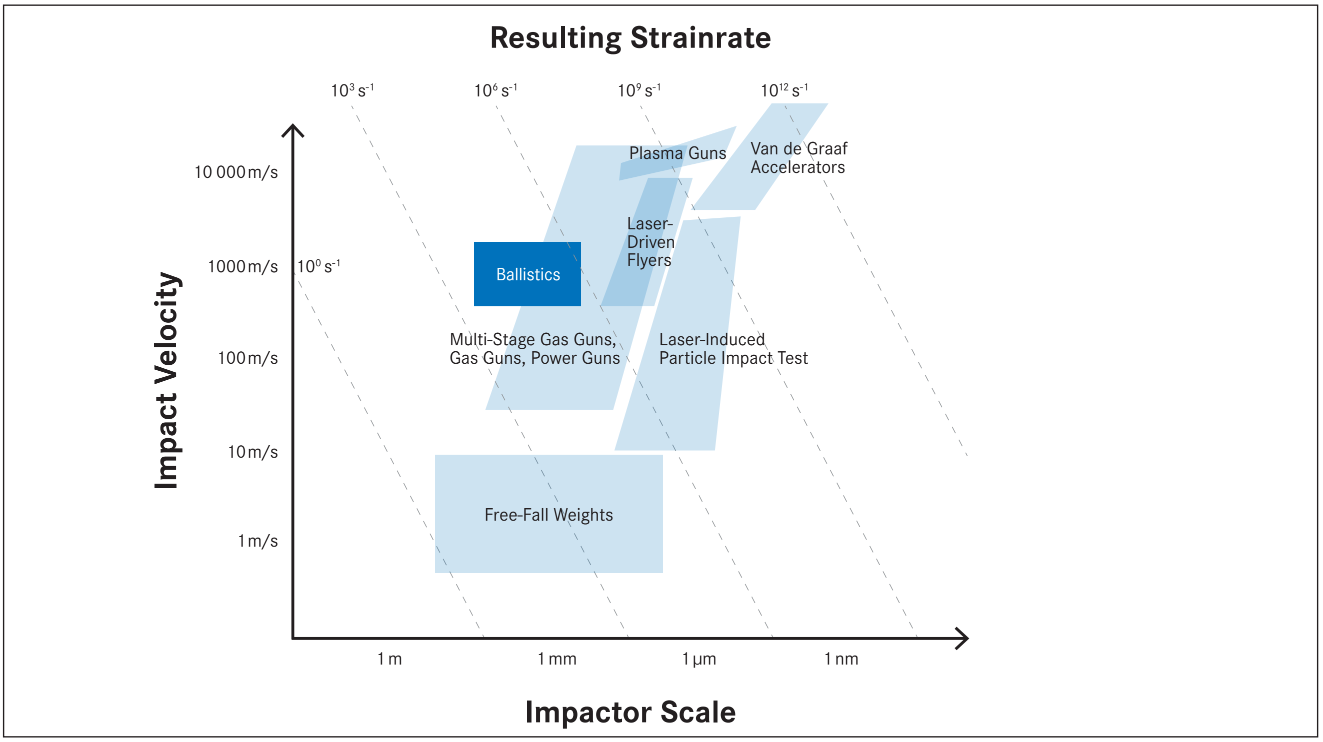

Figure 7: Impact testing techniques and several applications, along with lines of constant characteristic strain rates.

The typical temperature requirement for ballistic systems is -51 °C to 85 °C, according to MIL-STD-810G. To prevent delamination effectively and safely in the ballistic composite, the adhesive system must therefore demonstrate both high damping and high adhesion over the relevant frequency and temperature range. This minimizes the damage radius after the impact and increases multi-hit resistance.

For solutions developed to protect lower threat levels a stiff back layer can be useful inducing dwell effect on the ceramic strike face and combined with high bonding strength sufficient to avoid delamination caused by moderate energies.

The higher the threat level, the more important becomes the damping behaviour. Especially in STANAG 4 to STANAG 6 solutions the damping property is the key to reliability of the system. Forces caused by high energy impact shockwaves are so high, that. only energy absorption within the system can decrease the force and its propagation distance under a critical level for the adhesion.

7 Silane Epoxy Adhesives

Silane epoxy adhesives are hybrid systems containing a silane and an epoxy component. The silane component entails high damping behaviour over a huge temperature range. The epoxy component causes high strength bonding and stiffness. Combined in the hybrid system, this shows a suitability to a wider range of substrates than other adhesives.

Depending on the chosen monomers and the proportion of the components the overall properties of the resulting system can be specifically adjusted (Figure 8).

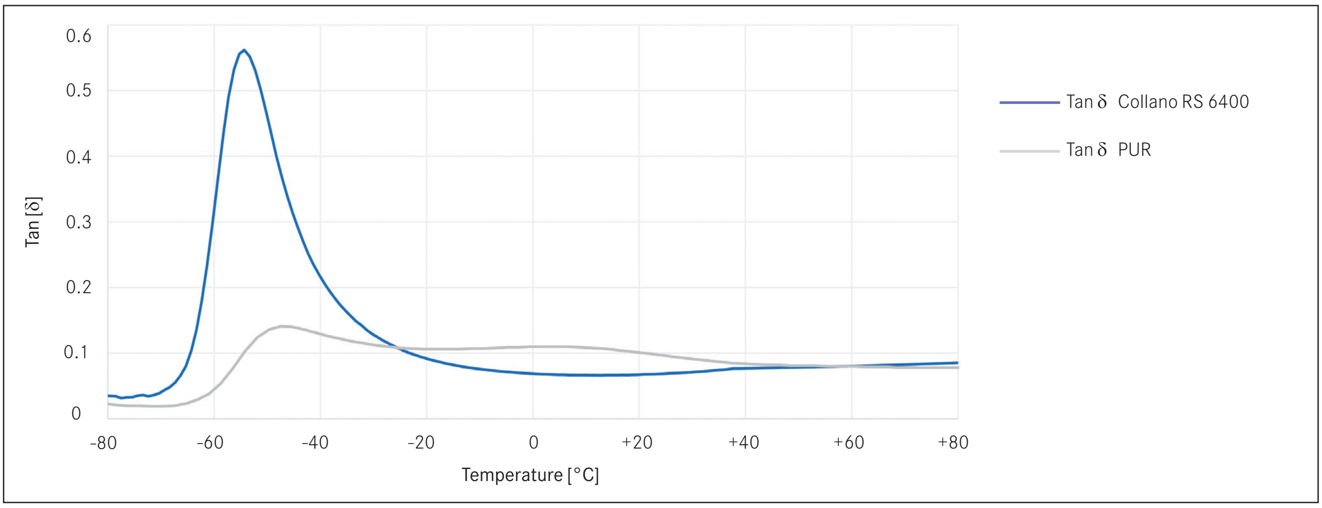

Figure 8: Loss factor at 1 Hz between -80 °C up to +80 °C from Collano RS 6400 (blue) vs. a typical PUR adhesive (grey).

PUR adhesives show constant behaviour over the temperature range, while Epoxy resins as very stiff systems do not have damping properties. One advantage of Silane Epoxy Adhesives is the significant higher damping behaviour around the glass temperature, which is 4 times higher than for PUR and plays a major role when applying dynamic strain to the system.

Silane Epoxy Adhesives – Strain Dependence

Beside the dependence on the temperature the damping of an adhesive is also influenced by the dynamic strain. By using special setups in Dynamic Mechanical Analysis (DMA), it is possible to determine the influence of dynamic strain to the adhesive's behaviour. The strain is given by oscillation with a defined frequency under constant temperature.

Doing those measurements under different temperatures creates results that combine temperature and mechanical influences simulating the circumstances and the behaviour of the adhesive in the ballistic application.

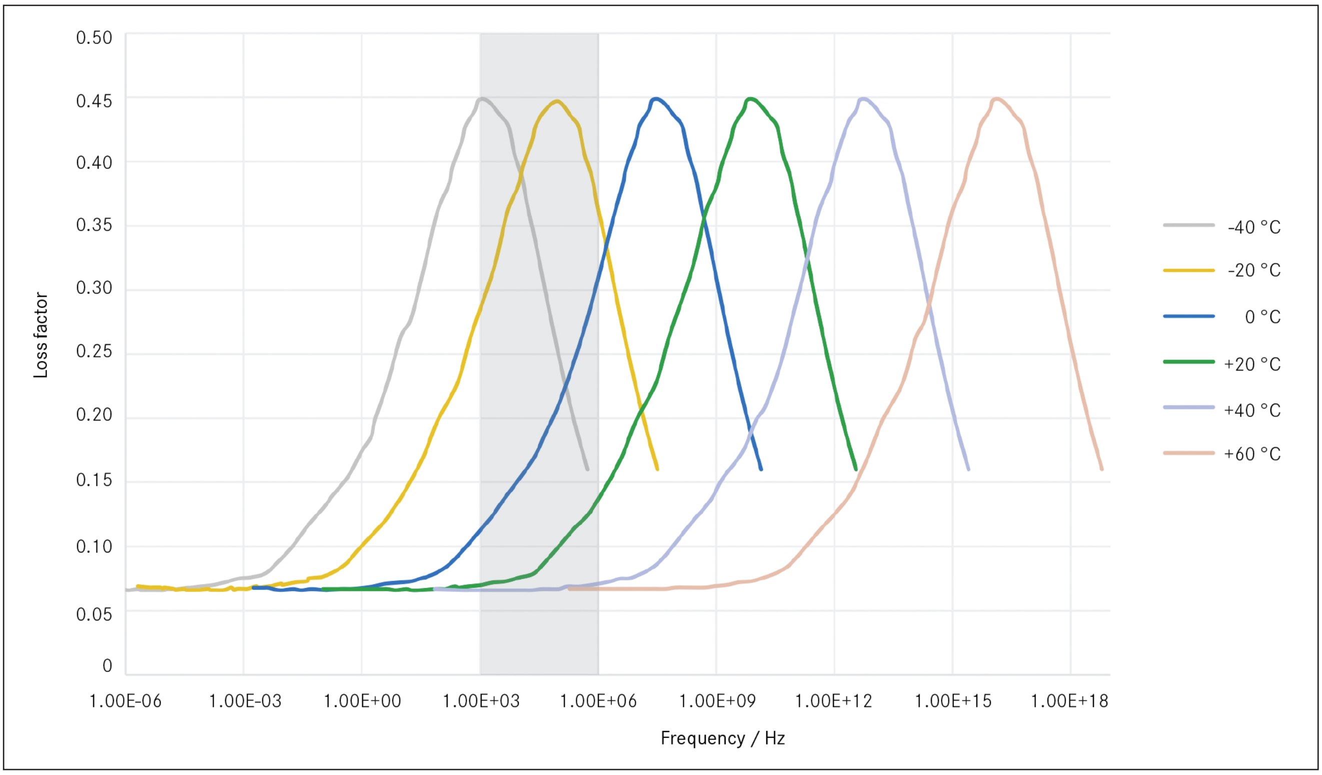

Figure 9: Loss factor of the Collano RS 6400 at different temperatures from DMA master curves.

The measurements under dynamic strain show the adhesives behaviour in the relevant frequency range of 10^3 to 10^6 Hz. Especially between -20 °C and +20 °C the tan δ peak of silane epoxy adhesives effects very high damping properties. For very low temperatures all adhesives show stiff behaviour. Here is the bonding strength the most important property.

Silane Epoxy Adhesives – Bonding Strength

Delamination only occurs when the force of the propagating wave exceeds the bonding strength of the adhesive. The bonding strength depends on the cohesion of the adhesion and the adhesion to the joined substrate. In composite armour systems the adhesive must bond metals, ceramics and polymeric backings. Therefore, the requirement to an adhesive is a wide bonding spectrum to all these materials as well as a sufficient bonding strength to each of them.

The following results show the shear strengths characteristic for the bonding strength of common adhesives on the relevant substrates of ballistic composites.

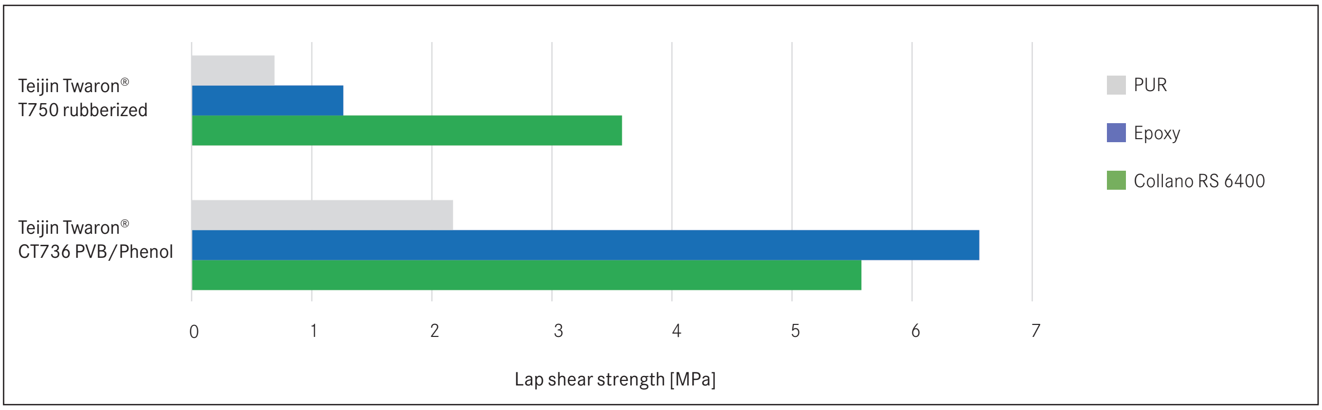

Figure 10: Lap shear strength of common backing systems, tested at room temperature and 2 mm/Min.

Silane Epoxy adhesives show excellent bonding strength on common backing systems (Figure 10). Especially on the rubberized system it is even superior to epoxy resins.

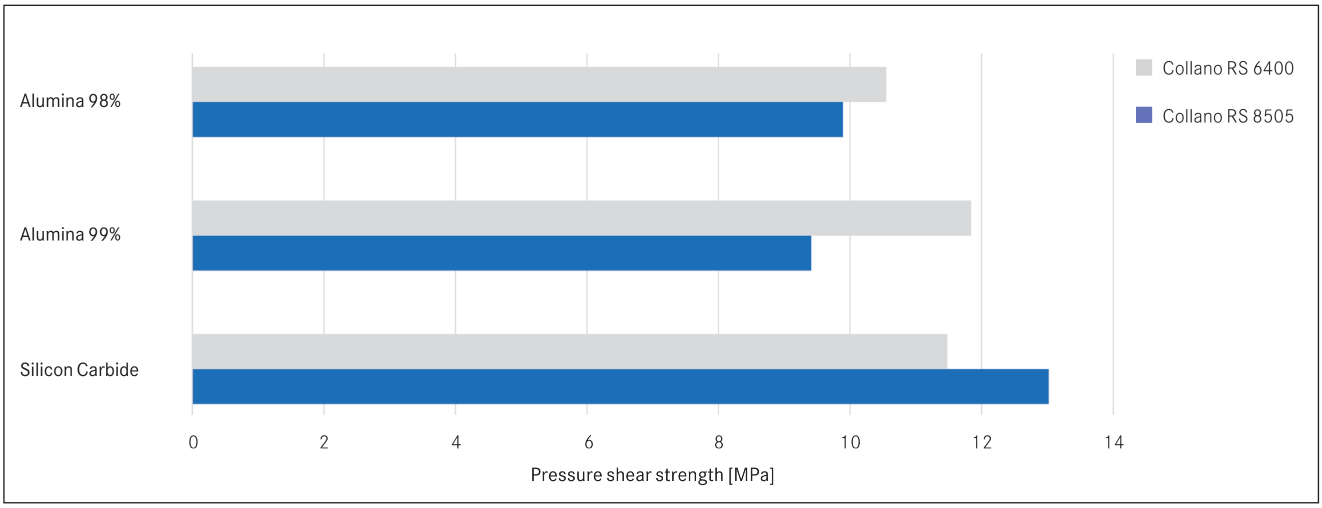

Figure11: Pressure shear strength on different ceramic substrates, tested at room temperature and 5 mm/Min.

Due to the Silane component Silane Epoxy Adhesives come with a wide bonding spectrum, also suitable for difficult substrates such as Silicon Carbide (Figure 11) and polymer matrix backing materials. Combined with high bonding strengths it is suitable for ceramic composite armour as well as spall liner applications.

8 Comparison of Common Adhesives

Summarizing all aspects an adhesive must fulfil in a ballistic system silane epoxy adhesives show significant advantages compared to other adhesive technologies (Table 1).

Adhesive	Bonding Strength	Damping Performance	Temperature Range	Bonding Spectrum	Work Safety
PUR	■	■■	■■	■■	■
Epoxy	■■■	■	■	■■	■■
Silane Epoxy	■■	■■■	■■■	■■■	■■

Table 1: Comparison of the performance of different adhesives for use in ballistic systems.

Also work safety and processibility are important arguments for choosing an adhesive. At the end all properties must fit into the ballistic system. There are various possibilities of combining ceramics, steel, backings and adhesives in different designs. Only a finally tuned system leads to the best possible protection.

9 Proved Performance

The effects of shockwave damping performance by silane epoxy adhesives are proved by several testing and are already successfully installed to popular land vehicle platforms. In shootings according to STANAG 4569 of ceramic composite armour it is demonstrated that the damping behaviour of silane epoxy adhesives avoids lateral delamination especially in high threat levels.

The following pictures show shooting results on composites built by 100 x 100 x 14 mm single tile alumina ceramics, shot with 14.5 mm x 114 API/B32.

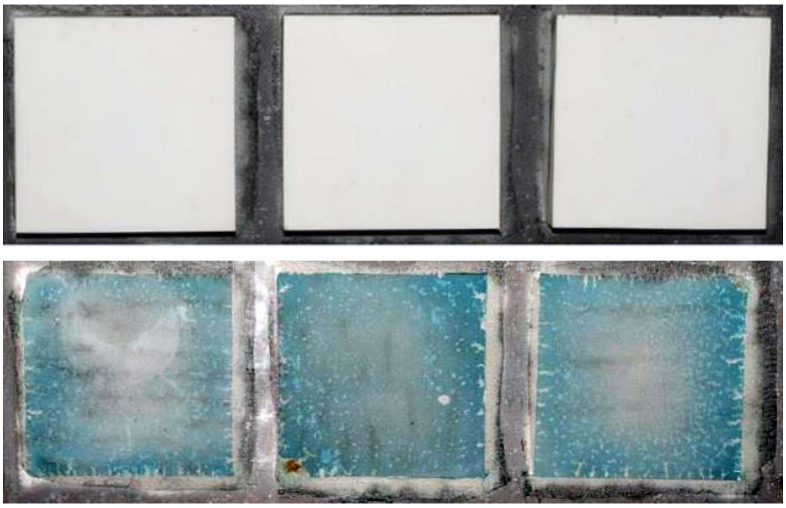

Figure 12: This shooting samples bonded by epoxy resin show overall delamination of the ceramic.

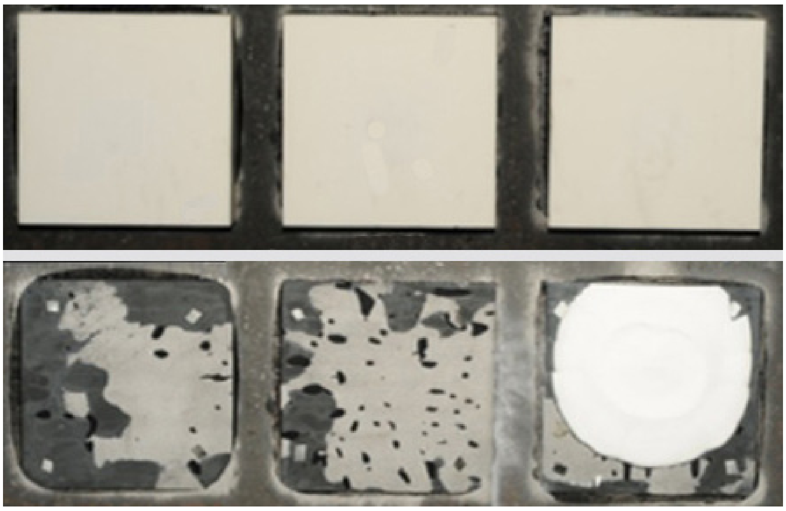

Figure 13: Also, bondings with PUR cannot avoid delamination of the ceramic composite.

Figure 14: Due to the combination of high adhesive strength and damping performance the targets bonded with silane epoxy are not delaminated.

Delamination effects caused by transversal shockwaves do not necessarily stop at the end of the ceramic tile. Shooting trials on multi-tile assemblies show that it can come to massive delamination especially by high calibre threats effecting multi-tile delamination. Compared to systems bonded with other common ballistic adhesives, the damage area can be minimized by using silane epoxy adhesives. Due to that effect the shockwave damping adhesive can increase the multi-hit performance significantly. The minimized damage range causes a higher intact protection area, a higher probability to withstand further shots and a higher survivability for the lives to be protected.

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