Experimental study about the influence of adhesive stiffness to the bonding strengths of adhesives for ceramic/metal targets

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Abstract

The aim of the investigations presented here was to understand how the stiffness of the adhesive affects the failure of ceramic tiles adhered to metallic backings. The working hypothesis was that varying the adhesive stiffness could have the same effect on the ballistic performance as a variation of the adhesive thickness.

Two different projectile/target combinations were utilized for ballistic tests in order to generate extremely different loading conditions. With targets consisting of 6 mm aluminum oxide ceramic and 6 mm aluminum backing, complete penetration occurred in each test with 7.62 mm tungsten carbide core AP ammunition at an impact velocity of 940 m/s. In contrast, with ceramic tiles of 20 mm thickness on 13 mm steel backing, no penetration of the ceramic occurred at the impact of a 7.62 mm ball round at 840 m/s.

Four different types of adhesive (high-strength till high-flexible) were tested in both configurations. The elongation of the adhesive layer, the deformation of the metallic backing and the failure of the ceramics were observed by means of a high-speed camera during the projectile/target interaction.

The results of the ballistic tests showed that a higher fracture strain caused a larger deformation of the backing compared to adhesives, which exhibit a high tensile strength and low fracture strains.

The experimental results indicate that the damage behavior of the ceramic/metal composites depends on the absolute elongation of the adhesive layer. This can be controlled either by the thickness or the stiffness of the bonding layer.

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1. Introduction

Beside excellent protection properties, weight is one of the important parameters of modern armor systems. To fulfill such boundary conditions the use of composite armor is an opportunity. Therefore modern lightweight armor consists of different classes of materials. A technique to combine the different materials is the use of adhesives. Thereby polyurethane and epoxy based adhesives are commonly used to bond ceramic armor systems [1]. Knowledge of the influence of the adhesive properties on target damage, deformation and the ballistic resistance is of importance for composite armor design. A parameter that is often discussed is the thickness of the adhesive layer. Zaera et al. [2] studied the influence of adhesive stiffness and thickness on ceramic damage and the deformation of the aluminum backing plate for targets. An optimum adhesive layer thickness with respect to the ballistic limit velocity for Al2O3-Al targets was observed by Lopez-Puente [3]. Prakash et al. [4] reported a non-monotonic variation of projectile penetration into the backing with variation of the adhesive thickness.

However, polyurethane and epoxy based adhesive systems show different mechanical behavior. Epoxy adhesives are less ductile than polyurethane ones, which exhibit a higher fracture strain. Former studies, e.g. by Zaera [2], showed that a thicker adhesive layer affected the performance of bonded ceramic/metal targets. A thicker adhesive layer led to an increased plastic deformation of the metallic backing and as a result of the plastic deformation resulted to a reduced projectile velocity. The damage pattern of the ceramics tiles also changed with a varying layer thickness. Zaera explained this behavior primarily by the increasing layer thickness [2]. However, due to the different elastic moduli of the adhesive materials, different absolute strains of the adhesive layer can occur. Therefore, the hypothesis was postulated that the

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adhesive stiffness could have the same effect on the ballistic performance of ceramic/metal targets. In order to verify this hypothesis, two different projectile/target combinations were utilized. In previously published work [2–4] only the extreme of complete penetration of ceramic/metal targets by an armor-piercing projectile was considered. In order to derive a better understanding of the influence of the adhesive stiffness, another test configuration was designed, where almost no penetration of the projectile into the ceramic occurs.

2. Experimental methods

2.1. Target description

Two types of targets were manufactured. Target type A, which is illustrated in Fig. 1, was derived from the work of Zaera [2] and Lopez-Puente [3]. The target was assembled from nine alumina tiles (ALOTEC 99 SB, CeramTec-ETEC GmbH, Lohmar, Germany) of dimensions 50.5 × 50.5 × 6 mm³, which were bonded to an EN AW-2017A-T 451 alloy aluminum plate of dimensions 200 × 200 × 6 mm³. Glass beads with a diameter of 0.3 mm controlled the thickness of the adhesive layer. The surface of the aluminum plate was cleaned by means of isopropanol before the adhesive was applied. To achieve a uniform tile pattern, the tiles were fixed on a PE plastic film first, cleaned using isopropanol and then transferred to the prepared aluminum plate.

Target type B is shown in Fig. 2. To avoid a significant plastic deformation, the target consists of three 100 × 100 × 20 mm³ alumina tiles (ALOTEC 98 SB, CeramTec-ETEC GmbH, Lohmar, Germany), bonded to a high hardness steel backing (Secure M 450, Thyssen Krupp) of dimensions 13 × 160 × 500 mm³. Glass beads also controlled the layer thickness of the adhesives. To provide a clean surface, the surface of the metal stripes was sandblasted and afterwards cleaned by isopropanol. The adhesives were applied to the backing and then the isopropanol cleaned ceramic tiles were positioned.

2.2. Adhesives

Four adhesives were utilized: Sikaflex® 553 2K (Sika Deutschland GmbH, Stuttgart, Germany), Scotch Weld™ DP 490 (3M Deutschland GmbH Industrie-Klebebänder, Klebstoffe und Spezialprodukte, Neuss, Germany) and Loctite® 9489 (Henkel AG & Co. KGaA, München, Germany), hereafter named AD1, AD2 and AD3. For target type B instead of AD1 a related Polyurethane adhesive Sikaflex® 221 (Sika Deutschland GmbH, Stuttgart, Germany), AD4, had to be used. In contrast to AD1 and AD4, which are polyurethane hybrids or polyurethane based adhesive materials, AD2 and AD3 represent epoxy based materials. The used adhesives differ not only in their chemical base but also in their mechanical behavior. The epoxy based adhesives AD2 and AD3 exhibit a high tensile strain and, compared to AD1 and AD4, lower fracture strains. Properties and applications of the used adhesives are summarized in Table 1.
2.3. Ballistic tests

In the tests with targets of type A, armor-piercing (AP) projectiles of caliber 7.62 mm with tungsten carbide core and a nominal impact velocity of 940 m/s were used. The deformation and the relative motion of the ceramic tiles and the backing were observed by means of a Shimadzu high-speed camera in a side view configuration at frame rates up to 125 kHz. The impact side of the ceramic tiles was observed simultaneously with a high-speed video camera of type Photron SA-Z at a frame rate of 100 kHz. Another Photron high-speed video camera was utilized to determine the residual velocity of the projectile.

For the tests with target type B, a 7.62 mm ball round with an impact velocity of 840 m/s was utilized and the target response was observed by means of a Shimadzu high-speed camera (side view). In contrast to type A, the effect of the ballistic impact was indirectly observed. Due to the fragmentation of the ceramic combined with a strong generation of dust, it was not possible to record the impacted adhesive layer. Thus the adhesive layer of a neighbor tile was observed. In Fig. 3(a) and (b), a schematic view of the experimental setup for target types A and B is shown.

To investigate the effect of the different adhesives several parameter were measured. By means of the high speed videos, the deformation of the adhesive layer and the metallic backing was evaluated. Also, the loss of the kinetic energy and the remaining backing deformation were analyzed.

### Table 1
Overview of used adhesive materials.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Commercial name</th>
<th>Target</th>
<th>Chemical base</th>
<th>Fracture train/%</th>
<th>Tensile strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD1</td>
<td>Sikaflex® 553 2K</td>
<td>A</td>
<td>Polyurethane hybrid</td>
<td>350</td>
<td>2.6</td>
</tr>
<tr>
<td>AD2</td>
<td>Scotch Weld™ DP 490</td>
<td>A, B</td>
<td>Epoxy based</td>
<td>2</td>
<td>48.0</td>
</tr>
<tr>
<td>AD3</td>
<td>Loctite® 9489</td>
<td>A, B</td>
<td>Epoxy based</td>
<td>64</td>
<td>13.2</td>
</tr>
<tr>
<td>AD4</td>
<td>Sikaflex® 221 2K</td>
<td>B</td>
<td>Polyurethane</td>
<td>500</td>
<td>1.8</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Target type A

Fig. 4 presents exemplary targets after the ballistic tests. While AD1 bonded tiles stayed adhered to the backing, the adhesive layer failed when AD2 and AD3 were used. Another considerable difference between the targets was the distribution of the used adhesives. In contrast to the pasty and tough AD1, AD2 and AD3 exhibit a lower viscosity. As a result AD2 and AD3 had the tendency to infiltrate the gaps between the ceramic tiles although the PE film kept them together. Especially AD3 showed this behavior. The degree of infiltration depending on the used adhesive can be also seen in Fig. 4. An analysis of the width of the infiltrated joints resulted in values between 0.1 and 0.3 mm. While the PE film kept the AD1 bonded tiles together, the AD2 and AD3 bonded tile patterns showed – at least partially – infiltration of the tile joints. The degree of infiltration with AD3 seemed to be higher compared to AD2. This means that an optical examination yielded 60% of complete infiltrated joints of AD3 bonded targets in contrast to 30% of complete infiltrated joints when using AD2.

To understand the different results of the ballistic test, the analysis is subdivided into four parts.

3.1.1. Projectile target interaction

Target type A is ballistically undersized against the used 7.62 mm AP projectile. Therefore the projectile penetrates the targets and only a minor part of the kinetic energy of the projectile...
projectile is transformed by the interaction between target and projectile. Seven AD1, four AD2 and five AD3 bonded targets were tested.

Fig. 5 shows a selection of photographs from the high-speed camera which observed the front of the impacted sample. The impact velocities were in the range from 922–949 m/s. Through the impact (Fig. 5(a)) the projectile tip was fragmented and the jacket removed. The projectile fragments were moving radially away from the point of impact and formed a circle with increasing diameter (see Figs. 5(b–d)). The fragments moved parallel

Fig. 4. Photographs of impacted ceramic/metal targets of type A: (a) bonded with AD1, (b) and (c) AD2, and (d) and (e) AD3; (b) shows the backside of the detached ceramic tiles.

Fig. 5. High-speed photographs of the front view of target type A bonded with AD1, (a) 0 μs, (b) 20 μs, (c) 40 μs, and (d) 60 μs after projectile impact. The bars indicate 5 cm.
to the ceramic surface without causing any visible damage to it.
The total penetration process took around 60 μs (Figs. 5(d) and 6(d)). The velocity of the projectiles after target penetration amounted to 594–755 m/s. This means about 46% of the kinetic energy of the projectile were transformed by the interaction between target and projectile.

In Fig. 6 a side view of a target type A is presented. After around 16 μs the first deformation of the metallic backing was observed (Fig. 6(b)). The diameter of the bulge increased and after a deformation of nearly 8 mm the stretched aluminum plates broke (Fig. 6(c)). An influence of the adhesive on the projectile erosion at the front of the ceramic and on the maximum deformation of the backing before failure was not discernible. However, the high-speed videos of the residual projectiles indicate an influence of the adhesive on the grade of projectile fragmentation. Fig. 7 shows high-speed photographs of the projectiles after target penetration. The high-speed photographs indicate a higher degree of fragmentation in case of the adhesives AD2 and AD3. However, due to the limited number of tests, a possible influence of projectile yaw could not be excluded. If only the direct projectile target interaction was considered, projectile damage seemed to be the only parameter affected slightly by the type of adhesive. A possible influence on the loss of kinetic energy might also be suggested by the experimental results. However, the variation of the data and the small number of tested samples make a conclusion difficult. The different compression moduli of the adhesives lead to different support of the ceramic by the backing. This could explain the damage variation of the projectiles. The compression moduli of AD1 is more than three magnitudes lower compared to AD2 and AD3, which results in a much weaker support of the ceramic through the backing and might explain the observed differences.

In contrast to the maximum bulging of the aluminum backing, the plastic deformation of the whole aluminum backings seems to be affected by the used adhesives. In Fig. 8 the
side view of an impacted sample is presented. Whereas the difference between AD1 (average: 63.4 mm) and AD2 (average 66.3 mm) bonded target isn’t obvious, the average deformation of AD3 bonded targets amounts to 77.2 mm. Even though the mechanical properties of AD1 and AD2 differ, the backing deformation seems to be unaffected. Therefore, another adhesive property should be considered. Both sound velocity (2240 m/s) and density (1.25 g/cm³) of AD3 surpass the values of AD1 (1360 m/s, 1.24 g/cm³) and AD2 (2200 m/s, 1.05 g/cm³). Therefore the more deformed backing could be explained by an improved acoustic impedance matching of AD3 compared to AD1 and AD2.

3.1.2. Deformation of adhesive layer

The main difference in the behavior of AD1 compared to AD2 and AD3 bonded targets was the failure of the adhesive layer when AD2 or AD3 were used. In these cases all tiles were detached from the backing after projectile penetration. By using AD1 a significant elongation of the adhesive layer occurred.

However, a difference between AD2 and AD3 should be also noted. On the one hand, the tiles bonded with AD2 detached without a quantifiable elongation of the adhesive layer but on the other hand, the point in time of detachment was earlier. Fig. 9 shows exemplary the time dependent development of the distance between backing and ceramic tile of AD2 and AD3 bonded targets (measured at Point 2, see Fig. 3(b)). In Figs. 10 and 11 high-speed photographs of the adhesive layer between backing and ceramic tiles are displayed. The spatial resolution is around 0.16 mm.

The curves in Fig. 9 indicate that the distance between backing and ceramic tile increased nearly linear after a period of time of about 100 μs. The high-speed photographs in Fig. 10 display the movement of the metallic backing while the tiles nearly kept their position. During the first 100 μs the layer thickness remained constant. The displacement of the backing, which can be recognized in a comparison of the backing position in Fig. 10(a) and (b), can be explained by the deformation of the aluminum. Due to the bending of the backing plate in the...
center, the observed edge was accelerated against the impact direction, which led to a short period of compression of the adhesive layer. After this short bending phase the whole backing moved in the flight direction of the projectile. This change of the direction of motion should have been transferred to the ceramic tiles by the adhesive. However, the direction of motion of the tiles didn’t change and the distance between backing and tiles increased. These observations in combination with the fact that the tiles were completely detached from the backing (See Fig. 4(c)) led to the conclusion that the AD2 failed adhesively at the metal glue interface and no significant elongation of the material occurred.

When AD3 was used the tiles didn’t detach instantly. As Fig. 10(c)–(e) illustrate, a period of tensile strain of the adhesive layer of nearly 50% was observed. The course of events – bending of the plate followed by acceleration and movement – was the same as with AD2 bonded targets. The elongation of the adhesive layer started with the movement of backing. However, the point in time was different for AD2 and AD3 bonded targets. The elongation of AD3 bonded targets started 36 μs (average value) later than compared to AD2. During the elongation the ceramic tiles kept their position. The elongation of nearly 50% correlates with the values of the fracture strain, too. The delayed elongation of the adhesive layer combined with the delayed deformation of the backing compared to both AD1 and AD2 could be explained by a better damping behavior and a higher Young’s Modulus of AD3. A possible compression of the adhesive layer couldn’t be resolved. The detachment of the tiles can be explained by both the low fracture strain and low adhesion strength of AD2 and AD3. However, the failure of AD3 after a longer time of strain indicates a higher adhesive strength compared to AD2.

The diagram in Fig. 12 and the high-speed photographs in Fig. 13 illustrate the behavior of AD1. The point in time of the beginning tension of the adhesive layer is around 18 μs later than AD2. A nearly linear increase of the backing tile distance was observed. In Fig. 13(e) the stretched adhesive layer is shown.

The maximum observed strain of nearly 250% is less than the reported fracture strain. The photographs show the same time depending backing displacement compared to AD2 and AD3 bonded targets; after bending, the backing moves in flight direction of the projectile. Therefore the adhesive is getting stretched. Afterwards the tiles, which move opposite to the backing, are stopped and drawn to the backing. The adhesive acts like a kind of elastic band. After less than 400 μs the distance between backing and tile remained constant. Several high-speed videos of AD1 bonded targets showed a partially adhesive failure of AD1 on the adhesive ceramic boundary. In contrast to AD2 and AD3 the adhesion strength between adhesive and ceramic seemed to be less than the strength between metal and adhesive. Fig. 14(a) supports this assumption. Around the impact site the adhesive layer seems to be intact and the embedded glass beads are visible. This indicates a potentially adhesive failure of the adhesive backing interface. However, the layer failed just partially. The tiles remained on the backing. The increased thickness of the adhesive layer after the stretching can be explained by partial fatigue and plastic deformation of the adhesive layer.

Table 2 summarizes the analysis of the adhesive layer deformation for all tested type A targets. The results presented above are consistent with the other tested targets. The deviations can be explained by variation of the kinetic energy and the projectile yaw. The higher deviation of the layer elongation is based on the low resolution of the high-speed camera compared to the adhesive layer thickness.
3.1.3. Central tile damage

The damage of the central tiles differed considerably depending on the used adhesive. Fig. 14 shows close-up photographs of the central tiles of the targets presented in Fig. 4. The bright spots in Fig. 14(a) are the glass beads which were used as spacer. While the central tile of AD1 bonded targets was massively fractured, the AD2 and AD3 bonded exhibited less damage. All tiles show cracks which propagated radially from the impact point. As mentioned above (3.1.1), the impact damage pattern was independent of the used adhesive. Therefore, the different damage conditions were caused by processes after projectile penetration.

Fig. 15 presents a selection of four high-speed photographs from the front view camera for type A targets. The amount of undamaged ceramic of the central tile depended on the used adhesive. As shown in Fig. 15(b) fractured ceramic of the AD1 bonded target was ejected and the tile seemed to buckle against the impact direction. However, the penetrating projectile also caused a lateral displacement of the large ceramic fragments. Since these ceramic parts were still attached to the backing by the glue, they were not ejected. Due to the lower Young’s Modulus of the hybrid polyurethane based AD1 the material was displaced laterally and impacted the adjacent tiles. This impact caused additional damage in the central tile (Fig. 15(b)).

The ceramic fragments which have no contact to the adhesive layer are ejected and form the second cloud of ceramic material which is ejected (Fig. 15(c) and (d)).

In contrast to AD1 bonded targets, all tiles are detached after nearly 150 μs by using AD2 and AD3. Therefore, potentially displaced ceramic material can be easily ejected. In addition the epoxy based materials AD2 and AD3 are significantly stiffer and exhibit higher fracture strength. Thus the displacement of the fractured center tile is also hindered. However another point seems to be crucial, too. As written above AD2 and AD3 are less paste-like than AD1. Especially AD3 shows the behavior to infiltrate the gaps between the different ceramic tiles. This adheres material acts like a frame. In combination with remaining adhesive at the back of the tile (see Fig. 4(c) and (e)) the tiles were kept together. Of course, a stiffer adhesive leads to a better support of the ceramic due to the backing. However in this case of a ballistic undersized target, this seems not to be a major parameter for the explanation of the behavior of the ceramic.

3.1.4. Surrounding tiles damage

In most cases AD1 bonded targets showed a cross pattern of fractured tiles. In contrast AD2 and AD3 bonded targets exhibited less damage of the surrounding tiles.

<table>
<thead>
<tr>
<th>Target Type A</th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting time of elongation of the adhesive layer/μs</td>
<td>117 ± 12</td>
<td>106 ± 16</td>
<td>142 ± 26</td>
</tr>
<tr>
<td>Time of failure of the adhesive layer/μs</td>
<td>–</td>
<td>106 ± 16</td>
<td>158 ± 26</td>
</tr>
<tr>
<td>Maximum elongation of the adhesive layer/%</td>
<td>330 ± 150</td>
<td>–</td>
<td>80 ± 40</td>
</tr>
</tbody>
</table>
As presented in Figs. 15(a)–(d), ceramic material of the center tile impacted the adjacent tiles. The displacement of fractured ceramic material began immediately after projectile impact. Fig. 5(c) and 5(d) clearly show the displacement of the surrounding tiles which are impacted by parts of the central tile. As a consequence of the ceramic fragment impact, the adjacent tiles broke, too. The ceramic on ceramic impact also explains the cracks parallel to the joints of the tile pattern. The maximum displacement of the surrounding was around 1.8 mm. This means that surrounding tiles in a lager pattern would also be affected. It should be noticed that the first cracks in the surrounding tiles were observed after 90–100 μs. At this point the backing around the impact site was already deformed. However, a displacement of the tile in projectile flight direction wasn’t observed and the diameter of the deformed backing area amounted to just 63 mm. Furthermore the main cracks were parallel to the joints. The edge tiles remained intact in most cases. Therefore it can be concluded that the main damage of the surrounding tile was caused by the displaced center tile.

The less flexible adhesives AD2 and AD3 showed a completely different behavior. The damage of the surrounding tiles was reduced markedly. Close-up photographs of AD2 and AD3 bonded targets presented in Fig. 16 show that cracks didn’t propagate into the surrounding tiles. The cracks stopped at the joint, which was filled with adhesive. A damage of the adjacent tiles wasn’t discernible. However some tiles remained bonded together. In three of the five samples the whole AD3 bonded tile pattern remained as one. As mentioned above the adhesive infiltrated the gaps between the tiles and kept the tiles together.

It is well known that the ballistic behavior of ceramic tile based armor could be improved by embedding the tiles in a ductile matrix [5]. A damage of the surrounding tiles primarily occurs when joints are not infiltrated with glue. In such cases the crack formation was observed after failure of the adhesive layer. Therefore, an influence of the deformed backing can be excluded. AD2 bonded targets showed no need of a complete infiltration of the gap between the tiles. Even a partial infiltration acted as a spacer between the tiles and reduced the fragmentation.

The effect of infiltration of the gaps between the ceramic tiles with glue is demonstrated in Fig. 17. No infiltration of the gaps resulted in a similar fracture pattern as observed with AD1 bonded targets.

Especially Fig. 12(b) illustrates the effect of the gap infiltration. While the tile to the right remained undamaged, the other adjacent tiles were fractured. In such cases crack formation was observed around 150 μs after projectile impact. This means that the ceramic pattern was already detached from the
backing. The cracks in the surrounding tile also seemed to be direct continuations of center tile cracks. These results support the conclusion of a high influence of the joint infiltration on the ceramic fracture pattern. The joint infiltration appears to be the major criterion for the damage of surrounding tiles.

3.2. Target type B

The configuration of type B targets was chosen in order to minimize the plastic deformation of the backing. For this reason, a thick ceramic tile was combined with a thick high hardness steel backing. Additionally, a threat with a significantly lower penetration capability was used. On the one hand, the kinetic energy was reduced, and on the other hand, a projectile material with a lower strength was used. The aim was to avoid plastic deformation of the backing and to generate only a shock loading of the adhesive layer. As mentioned above, an observation of the adhesive layer of the impacted tile was difficult. Instead, the adhesive layer of the not impacted tiles was observed, where only loadings in the elastic regime were expected. Fig. 18 shows a photograph of impacted targets.
The projectiles didn’t penetrate the targets. All impacted tiles showed radial cracks and a remaining fracture conoid. Due to the lower stiffness of AD4, the cracks were farther opened compared to the targets with the stiffer adhesive AD3, which kept the fractured material closer together. However in both cases the fragments could be removed easily. In case of the AD2 bonded tile, just the ceramic conoid stayed attached to the metallic surface.

Besides the fracture pattern, the backing displacement could also be used to evaluate the effect of the impact. The position–time histories of backing displacement are presented in Fig. 19 for the different adhesives. The positions of the measurement points are shown in Fig. 3(b). The time curves of the displacement are comparable to those of type A targets. After a short bending period the back side of targets was moving in the impact direction. However the bending of the steel backing as well as the total displacement was smaller. This can be explained by: the lower kinetic projectile energy, the higher mass of the type B targets and the higher elastic modulus of the steel.

The displacements were very similar for AD4 and AD2 bonded targets, whereas in the case of AD3 smaller displacements were observed. Since the velocity of the projectiles was almost the same in all tests (between 829 m/s and 843 m/s), the result could be explained by a stronger dampening characteristics of AD3 compared to the other adhesives, and higher energy absorption through elastic and plastic deformation. The similar displacements observed at measuring point 3 could be explained by the proximity of the measuring point to the target mounting.

While the center tile was fragmented, the other ceramic tiles remained attached to the metallic surface with the AD4 and AD3 bonded targets. With AD2 bonded targets, all tiles, even the ones that were not hit, were detached from the backing. In Fig. 20 high-speed photographs of the adhesive layer between steel and ceramic are shown. Compared to type A targets, not only the distance between tile and backing increased slower but also the maximum distance of 1.84 mm was smaller. The corresponding time curve is presented in Fig. 21. In case of AD2 bonded targets a relative velocity of 8 m/s between backing and ceramic was determined by linear regression, whereas a relative velocity of 25 m/s was determined for type A targets.

The point in time of failure of the AD2 adhesive layer was difficult to determine. The backing to tile distance increased slowly and the position of the tile didn’t change. An elongated adhesive layer could not be observed. The photographs of the impacted targets (Fig. 18(b)) also indicate an adhesive failure of
the adhesive-metal interface. Only the fracture conoid remained attached.

In contrast to target type A, with target type B the AD3 bonding layer did not fail. Fig. 21 shows the time dependent distance between tile and backing for AD3 and AD4. The maximum elongation of the AD3 was around 50%. This value corresponds to the reported fracture strain. The mean relative velocity between backing and tile was lower compared to the AD4 bonded target. The higher Young’s Modulus of AD3 reduced the total strain of the adhesive layer. Moreover, the strain rate was also reduced compared to target type A. A rough estimate calculation yielded strain rate that was one order of magnitude lower. This is a possible explanation for the fact that the tiles remained attached. Fig. 22 presents selected high-speed photographs of the maximum elongated adhesive layer of AD3 and AD4 bonded targets. The mechanical properties of AD4 are comparable to AD1. A maximum elongation of nearly 400% was observed.
3.3. Summary of the results

The results with both target types A and B indicate an influence of the adhesive on the ballistic performance of bonded ceramic/metal targets. An elastic deformation of the adhesive seems to be necessary to compensate the displacement of the backing, especially AD2, which exhibits a high tensile strength combined with a high stiffness failed independent of the tested configuration. In the tests to target type A the projectile perforates the target with a loss of only about half of its kinetic energy. The fragments of the impacted tile were strongly displaced. The shown differences of the fracture patterns were indirectly caused by the different adhesive stiffness. Of course a lower adhesive stiffness allows a larger displacement of the adhesively bonded fragments. However, the results indicate that the ability of the adhesives to infiltrate the gaps between the ceramic tiles determines the grade of damage in the tiles surrounding the impacted tile. The experimental results show that just a partial infiltration of the joints between the ceramic tiles already leads to a stop of crack propagation. The adhesive acts like a spacer and prevents displaced ceramic material of impacting surrounding tiles. Furthermore the infiltrating adhesive represents a confinement which may hold together fragmented tiles.

Without such infiltration the fracture patterns seemed to be comparable independent of the adhesive stiffness. Targets bonded with other flexible adhesives exhibited damage patterns similar to AD3 bonded targets, without failure of the adhesive layer. A possible increasing of the layer thickness leads to a higher amount of adhesive and therefore to an increasing tendency of infiltration.

The very similar fragmentation of the tiles with target type B, independent of the used adhesive, supports the results. The stiffness only affected the degree of opening of the cracks. However, the stiff adhesive didn’t compensate the backing displacement. Due to the design of the type B targets, a lower loading was generated. Therefore the adhesion strength of AD3 remained sufficient.

As shown in Figs. 9, 12 and 21 the distance between tiles and backing remains constant at the first 100 μs. Considering the time required for the waves to travel through the target, which can be estimated to 15 μs according to their longitudinal elastic wave speed, the observed phenomena seem to be caused by other effects. This supports the assumption that the observed phenomena are induced by the backing deformation.

It has to be noticed that just an edge of the target was observed. For the interpretation of the results concerning target type B, this fact hadn’t be taken into account, thereby the load of the adhesive was just caused by the backing vibration and not directly by the impacting projectile.

Target type A represents another issue. At the impact point the projectile destroyed also the adhesive layer. As written above, backing deformation seems to be the reason of the observed effects. Therefore the observation of the edge seemed to be sufficient. Of course the amount of the separation isn’t uniform across the diameter of the target. The massive deformation of both backing and ceramic tile around the impact point led to the detachment and/or damage of the adhesive. Thus the detachment seems to be caused by the backing deformation in combination with an insufficient adhesion strength; the observation of the edge seemed to be useful. The higher degree of deformation near to the impact point just leads to an earlier detachment. Of course the elongation of AD1 will be increased near to the impact point compared to values which are measured at the edge. However, the phenomenon is the same.

4. Conclusion

Two kinds of ceramic/metal targets were tested to investigate the adhesive stiffness influence on the ballistic behavior of ceramic/metal targets: perforation and shock load of the adhesive layer. The tested hypothesis was that absolute elongation of the adhesive layer determines the ballistic behavior of adhesively bonded ceramic/metal targets. It was shown that stiff adhesives didn’t compensate a high displacement of the metallic backing. From the point in time when the deformation of the adhesive layers began, it could be concluded that the observed detachment of the ceramic tiles was caused by the backing deformation.

The higher grade of damage in the impacted ceramic tile patterns in case of flexible adhesives was caused indirectly by the lower elastic modulus, which allows higher displacements of the ceramic fragments. However, similar damage was observed with stiff adhesives. Thus, the grade of joint infiltration turned out to be a crucial parameter. This means that the overall fragmentation of the impacted ceramic tile pattern is determined not only by the mechanical properties but also by the rheological parameter of the adhesive. Tests at a lower loading rate also indicated a rate dependency of the adhesion strength.

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