Two ballistic test methods combined; residual energy method and digital image correlation (REM/DIC)

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Abstract. In order to determine the ballistic efficiency of armour materials and armour systems several ballistic tests are available. In most tests only a binary test result is obtained; perforated or partially penetrated armour. TNO has used an alternative test method in which the material or armour system to be tested is always overmatched (sample perforated). The kinetic energy of the residual projectile is calculated from its mass and velocity. This kinetic energy is subtracted from the kinetic energy of the projectile before impact to obtain the projectile energy loss created during target perforation. This, so called, Residual Energy Method (REM) can be used on bare armour materials, as well as on complete armour systems and allows to determine changes in ballistic efficiency due to misuse, previous shots, aging, temperature changes, etc.When the target is not (yet) overmatched the response of the target can be determined using a digital image correlation (DIC) technique. For this method a speckle pattern is applied on the rear of the target or on a backing material. Two high-speed video cameras (each with a different angle towards the target) record the speckle pattern during and after projectile impact. These two video recordings are used in a post-processing software package that calculates the axial deflection and strain in the layer that holds the speckle pattern. From the time resolved data the distribution and history of the deflection, strains, velocities and strain-rates can be obtained. DIC data can be used to better understand the projectile-target interaction as well as for the validation of projectile-target interaction simulations. By combining these test methods, a useful test result is always obtained as for a perforating shot mainly the REM results are of importance, while for a stopped projectile the DIC results provide the relevant information.

1. INTRODUCTION

For many cases of projectile-target interactions typically the dynamic material properties of both the projectile materials and those of the target systems are unknown. Also, the failure mechanisms and failure loads/strains are unknown for the conditions that these materials experience during high-speed impact. This makes it hard to use (engineering and computer) models for the prediction of the projectile to target interaction, as these tools require these parameters as input variables for the calculation.

Materials and armour systems are generally ballistically tested. Such experiments may provide the depth of penetration (DoP) in a semi-infinite thick block, or a velocity of the projectile that has 50% chance of perforation (V_{50}). In both cases there is no role for the residual projectile, other than perhaps the (residual) velocity of it. Additionally, the DoP method was shown to suffer from a very large variation in test results [1].

Ballistic tests result in the interaction of two bodies colliding; the projectile and the target. In general, more attention in these tests is paid to the consequence for the target (dent or hole size, cracks, delamination, fragments, etc). Less attention is given to the residual projectile as it is normally not soft recovered. However, the residual projectile status (whether it is intact, deformed, broken or eroded) provides important information on the projectile-target interaction. Hence, in this work we will describe a soft recovery method for residual projectiles. This allows the residual projectile to be recovered after each test.

After measuring the mass and velocity of the residual projectile or rather the core of the armour piercing bullet (AP-core), its kinetic energy can be calculated and compared to that of the intact projectile (or AP-core) just before impact on the target. From the difference in mass, the amount of erosion of the projectile or core is obtained. Such information can be used for the ranking of targets and can also be used to analyse such data and learn about the projectile-target interaction. In order to determine the ballistic efficiency of ceramic tiles and armour systems the Residual Energy Method (REM) test has been used in the European Defense Agency category B projects CERAMBALL and CERAMBALL II. In

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these projects most ceramic based armour systems are rated on their ballistic efficiency against Armour Piercing (AP) projectiles. Only the core of the projectile is considered as it is assumed that the projectile jacket is too soft to play a role in the penetration process. Targets consisting of a bare ceramic tile or ceramic based armour were impacted using regular AP projectiles (0.30” or 0.50” AP) with a constant impact velocity. A residual projectile catching device allowed to retrieve the residual projectile parts. However, this device used water (in a horizonal metal tube) for the soft recovery and this proofed to be a problem for many of the ballistic test centers involved.

Additionally, we can also learn from interactions in which the projectile is stopped. The impact of the projectile on thick targets frequently results in a dent formation and hence a large out-of-plane deformation of the target or backing material. The target accelerations, its top velocity and strain-rates are extremely high in high-speed impact tests and it has long been quite hard to perform measurements of such parameters. However, nowadays with the use of high-speed video and digital image correlation (DIC) software it is much easier to determine the distribution of such parameters over the rear surface of targets and backing materials.

By combining these two test methods, REM and DIC, useful information is gathered for each test; in case of target perforation the residual projectile is caught and weighted, while in case the projectile is stopped the DIC method allows to record many parameters of the target from the rear.

In this paper we will first focus on the residual energy method. The digital image correlation is described in a following chapter.

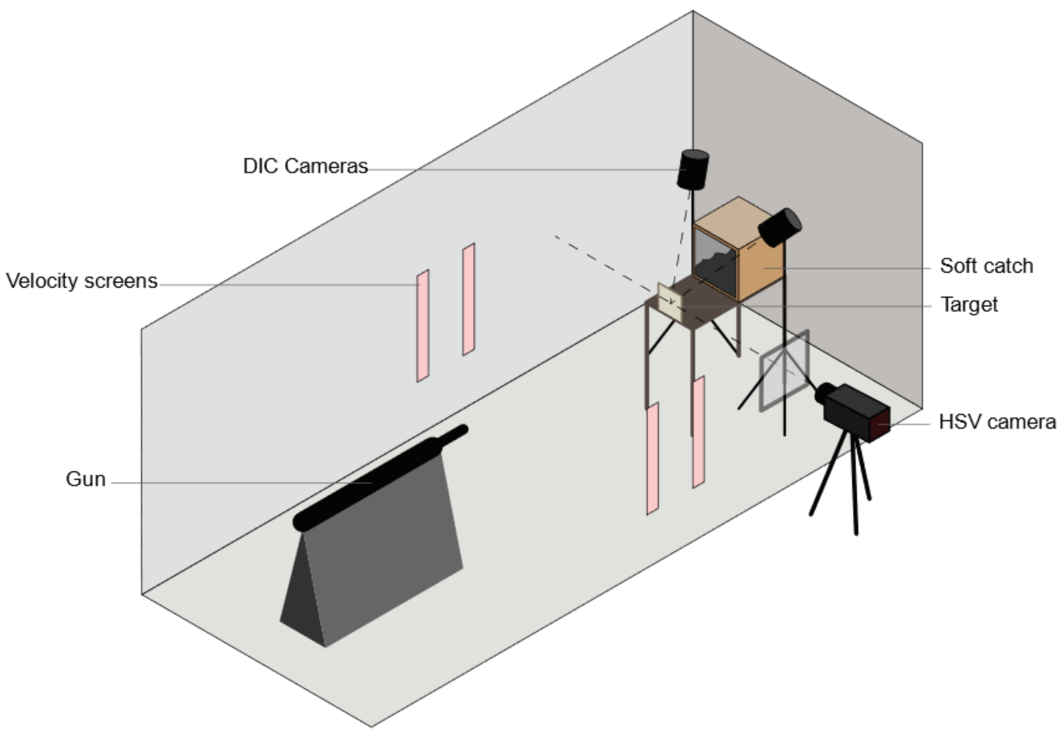

Figure 11. Test setup for the combined test method REM and DIC.

2. RESIDUAL ENERGY METHOD

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The REM ballistic testing method more specifically determines the degree of erosion and deceleration of the projectile after target interaction compared to traditional testing methods. Figure 11 schematically shows the test set-up inside a ballistic testing range. Specifically for the REM test are the high-speed video camera, the projectile soft catch device and the velocity screens. The selected projectile is launched by a stationary gun. The projectile velocity is measured using the velocity screens (dividing the screen distance by the time-of-flight of the projectile between the screens). The high-speed video (HSV) camera and flashlight are triggered by the signal of a laser screen and starts recording after a pre-determined delay time. The camera is positioned outside of the shooting range and records the normal impact process in side-view through a transparent armour window. The frame rate used in the recordings should be no less than 50.000 frames per second and preferably between 200.000 and 500.000 fps. The optical lenses used should provide a clear image of the target (in side-view), as well as the fragment cloud (until 10 to 20 cm behind the target).

From these side-view recordings not only the impact on the tile, but also the fragment cloud behind the tile can be observed. This allows measurement of the velocity of the tip of the ceramic fragment cloud. The latter is assumed to be equal to that of the residual projectile. A scenario where an AP bullet interacts with a ceramic tile is schematically shown in Figure 12. The high-speed video results also allow the determination of the main dimensions of the fragment cloud.

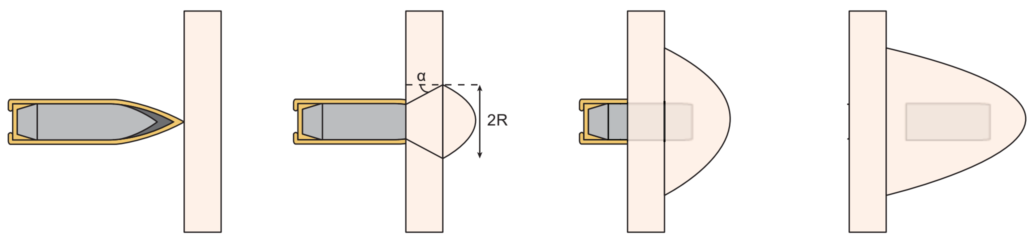

Figure 12. Schematic view of high-speed video images at various interaction times.

After the residual projectile has been caught, it should be recovered from the soft catch medium and weighted. Before weighting, the AP core fragments should be separated from any other particles that may have been entrapped, such as jacket parts and target particles. The residual velocity of the projectile can be obtained from the high-speed video recording. It is assumed that the velocity of the residual AP core is equal to that of the tip of the fragment cloud. The kinetic energy ($E_{kin,out}$) of the residual core is obtained through:

$$E_{kin,out} = 0.5 * m_{core,residual} * v_{cloud}^2 \tag{1}$$

Where $m_{core,residual}$ is the weighted mass of the residual projectile core fragments and v_{cloud}^2 is the measured velocity of the fragment cloud.

Based on the masses and velocities of the AP core before and after impact on the ceramic tiles the kinetic energy loss ΔE_{kin} of the AP core can be calculated:

$$\Delta E_{kin} = 0.5 * m_{core} * v_0^2 - 0.5 * m_{core,residual} * v_{cloud}^2 \tag{2}$$

Where m_{core} is the initial AP core mass and v_0 the impact velocity.

The material or armour system can be ranked using the fraction of energy loss of the AP core they provide.

$$Ballistic\ efficiency = \frac{\Delta E_{kin}}{E_{kin,0}} \tag{3}$$

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Where $E_{kin,0}$ is the kinetic energy of the AP core before impact.

As the REM uses mass and velocity of the bullet before and after penetration, it can be applied to any armour system (a single plate or a complete armour system) as long as it is overmatched by the projectile. In this paper some experiments are presented considering bare ceramic tiles, as well as ceramic tiles with various backing materials using 7.62 AP bullets. Figure 3 shows an example of recovered core fragments of the 7.62 AP M2 bullet along with ceramic tile fragments that are formed during the projectile-target interaction. The AP core fragments have been caught using a revised projectile fragment catching device that is shown in Figure 4. In this new device, the earlier wet projectile capture method is replaced by a dry system, which is more friendly for the shooting range environment.

The new projectile fragment catcher makes use of a granular elastomeric material (granulated car tires) situated in a steel tube with a diameter of 33 cm and a length of 130 cm. The granulate filled tube is in horizontal position during a shot and positioned about 30 cm behind the target (this allows room for the high-speed video recordings directly behind the target). After a shot, the tube is rotated in vertical position and opened to allow the granulate to pour down into a container through a magnetic sieve. This sieve separates any ferro-magnetic particles from the granulate, hence the bullet fragments (steel and hard metal) are separated from the polymer and ceramic particles. The sieve section can be taken away and this allows the bullet fragments to be collected for each shot. After this separation the sieve is replaced in the set-up and after the metal tube is back in horizontal position. It is refilled with granulate using an industrial vacuum cleaner and hose. This avoids the experimenters having to fill the tube by hand after each shot, which saves a lot of work and time. It was proved that this system has a cycle time (time between shots) of less than 10 minutes.

Table 1 shows the results of a test series (using 7.62 AP P80 bullets) performed on 10 mm thick bare B_4C tiles that were made in various batches using starting powder of different particle sizes (0.5, 1.4, 2.5, 7 and 20 μm) at RHP Technology in Austria. From each batch 3 samples were tested to obtain an understanding of the variations in the REM test and allow an average ballistic efficiency to be determined for the ceramic (using equation 3). The results of the (average) ballistic efficiency of these tiles are shown graphically in figure 5. The B_4C particle size scale is logarithmic as this better shows the trend observed; the ballistic efficiency increases with decreasing particle size of the starting B_4C powder. However, below a particle size of about 1 μm the ballistic efficiency decreases rapidly and is again comparable to that of the coarsest starting powder with a particle size of 20 μm.

Figure 13. Residual fragments of the 7.62 AP core (in bag) and ceramic tile recovered from a REM test

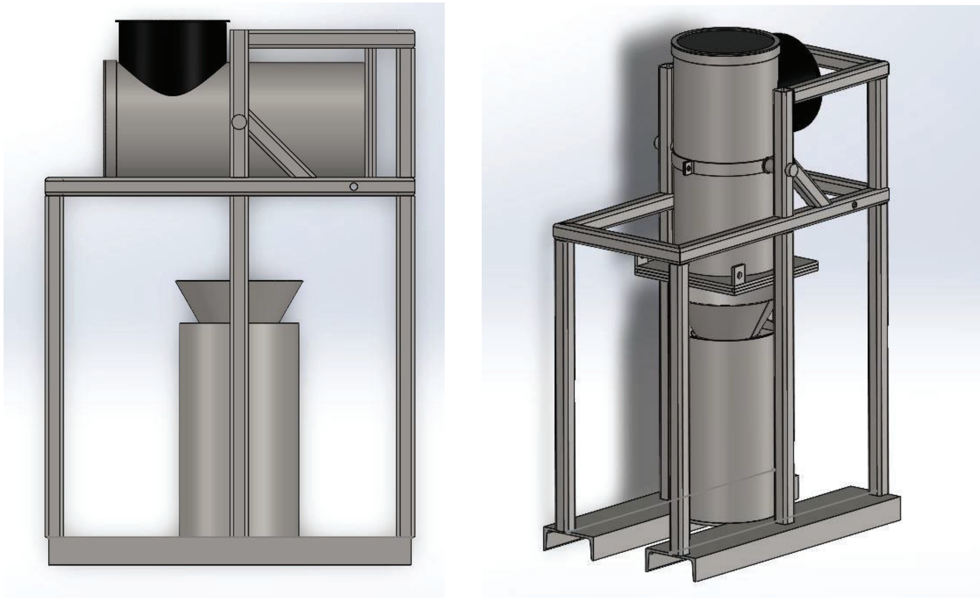

Figure 4. Residual projectile fragment catching device in shooting position (left) and after a test for separation of metal fragments using a magnetic sieve (right).

Table 1. Overview of REM test results for bare B_4C tiles

Sample Code	thickness [mm]	Composition	AD [kg/m2]	%TMD	Vin [m/s]	Vres [m/s]	Mres [gram]	E0 [J]	Eres [J]	ΔE [J]	BMEF [Jm2/kg]	BERatio [%]	average BE [%]
B11-01	9.70	B4C Grade 1 0.5 µm	24.5	99.2	820	631	3.29	1244	655	589	24	47	
B11-02	9.70	B4C Grade 1 0.5 µm	24.5	99.2	816	640	3.09	1232	633	599	24	48	
B11-04	9.70	B4C Grade 1 0.5 µm	24.5	99.2	819	638	2.94	1241	598	643	26	51	**48**
B12-02	9.80	B4C Grade 2 1.4 µm	24.6	98.2	827	566	2.49	1265	399	866	35	69	
B12-03	9.70	B4C Grade 2 1.4 µm	24.6	98.2	822	599	2.32	1250	416	834	34	66	
B12-04	9.70	B4C Grade 2 1.4 µm	24.6	98.2	818	664	2.84	1238	626	612	25	49	**61**
B13-02	9.90	B4C Grade 3 2.5 µm	24.8	98.80	534	-	2.84	528	-	-	-	-	
B13-03	9.90	B4C Grade 3 2.5 µm	24.8	98.80	823	616	2.89	1253	548	705	28	56	
B13-04	9.90	B4C Grade 3 2.5 µm	24.8	98.80	823	609	2.88	1253	534	719	29	57	**57**
B14-01	10.10	B4C Grade 4 7 µm	25.4	98.5	810	624	3.04	1214	592	622	24	49	
B14-02	10.10	B4C Grade 4 7 µm	25.4	98.5	823	594	2.88	1253	508	745	29	59	
B14-04	9.95	B4C Grade 4 7 µm	25.4	98.5	822	628	2.89	1250	570	680	27	54	**54**
B15-01	10.10	B4C Grade 5 20 µm	25	96.5	821	628	3.02	1247	596	651	26	52	
B15-03	10.00	B4C Grade 5 20 µm	25	96.5	822	637	2.91	1250	590	660	26	52	
B15-04	9.90	B4C Grade 5 20 µm	25	96.5	828	658	3.28	1268	710	558	22	44	**49**

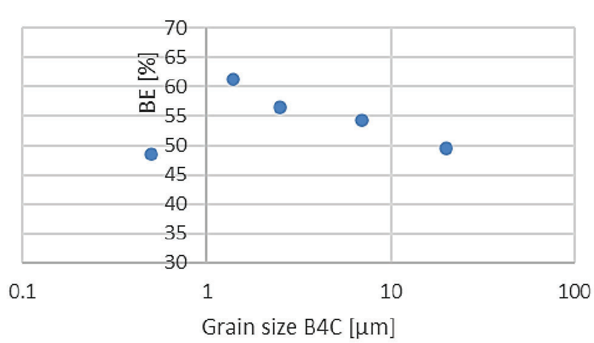

Figure 5. Graph showing the ballistic efficiency of B_4C tiles as a function of the particle size of the starting material (B_4C) powder as determined using a REM test series.

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3. DIGITAL IMAGE CORRELATION

Digital Image Correlation is a method that allows the determination of motion of the rear side of a target over a wide area. In order to measure the complete target response, it is best when the projectile is stopped by the target, as this leaves the rear of the target largely intact during the interaction process. The DIC method makes use of two simultaneous (high-speed) video recordings of the target rear each at a separate viewing angle. The area to be recorded should have a large number of random discrete speckles with a high contrast to the target surface (speckle pattern). An example of such a pattern is given in Figure 6. From the stereographic high-speed video recordings, a post processing DIC software package is used to determine the out-of-plane deflection and velocity, strain distribution and strain rate history. Such parameter histories can be used to validate finite element simulations and provides the strain and strain rates experienced by armour materials during the interaction with an impacting projectile. For the DIC recordings the rear of the target should be illuminated with two lights behind and aimed at the target.

When the REM tests are performed in combination with digital image correlation, the use of flashlights should be avoided, as their intense light flash will overexpose the DIC images. Instead, a continuous light source is used for the high-speed video recordings.

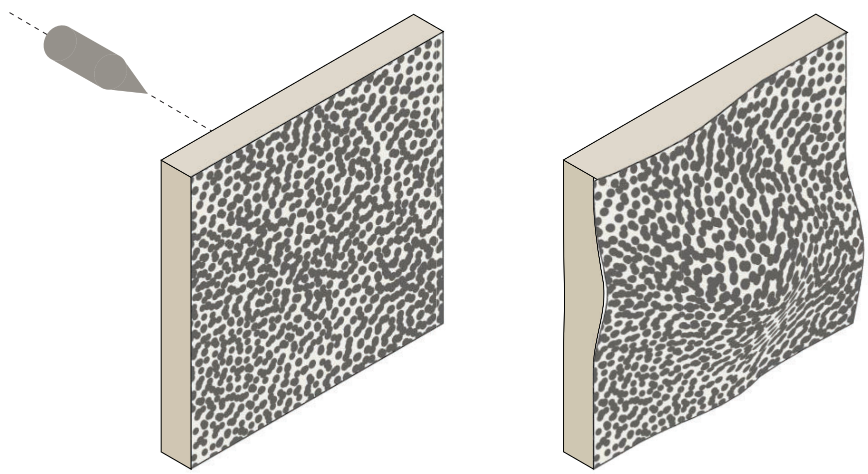

Figure 6. DIC speckle pattern target after a partial penetrated projectile interaction

Figure 6 also shows the interaction between a projectile and a speckled target. The reaction of the rear of the target in the second image occurs at approximately 0.1 ms after impact. The speckles are recorded by the DIC cameras at each video frame. The DIC software translates the speckle recordings into panel deflection, velocities, strains, and strain-rates of the rear of the target. The resulting time resolved data can be presented in graphs. Points on the target surface can be selected to prompt the required data from the software. An example of a deflection graph is presented in Figure 7. A ranking of ballistic efficiency could be based on a specific measured parameter by comparing various target responses using identical impact conditions. Prediction of blunt injuries can be done using the blunt criterion [2, 3, 4] or the viscous criterion [5, 6]. The maximal velocity of the backing is an important parameter in injury level calculations like behind armour blunt trauma (BABT).

The DIC data can also be applied to gain knowledge about the projectile-target interaction(s) and failure mechanisms that are involved, e.g., material properties largely influence the ballistic behaviour. From DIC data the mechanical behaviour of the material, like straining capability at high strain rates and the possibility to absorb energy by panel deflection, can be further investigated. Figure 8 and 9 show examples of the axial velocity and strain history, respectively, for a bullet (7.62 AP P80) hitting at 800 m/s on an 8 mm thick alumina tile with an 11 mm thick aramid backing material.

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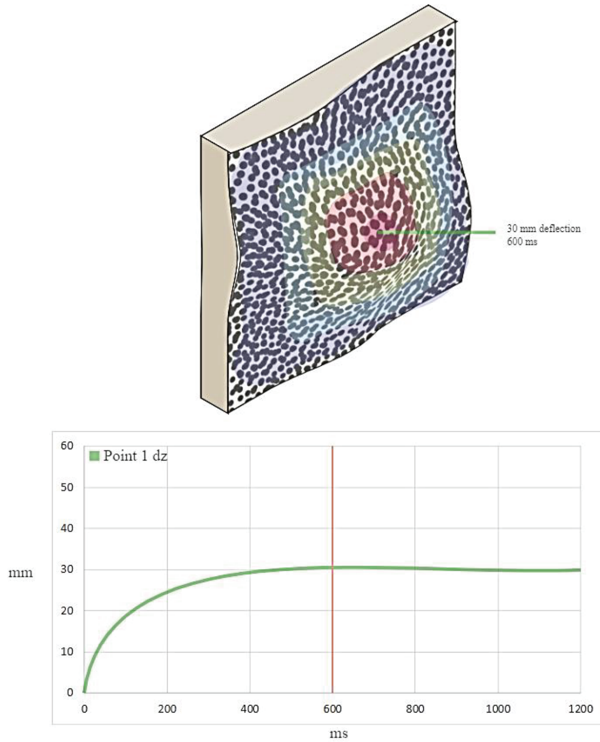

Figure 7. Example of DIC software image (top) with the corresponding graph (below) of the target displacement in time at the indicated position in the image in green.

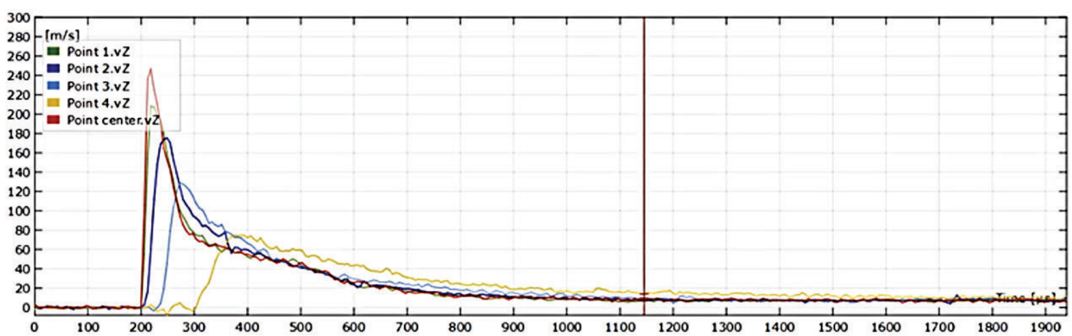

Figure 8. Example of a DIC result: velocity history of various points on an aramid backing plate; time scale is microseconds (µs).

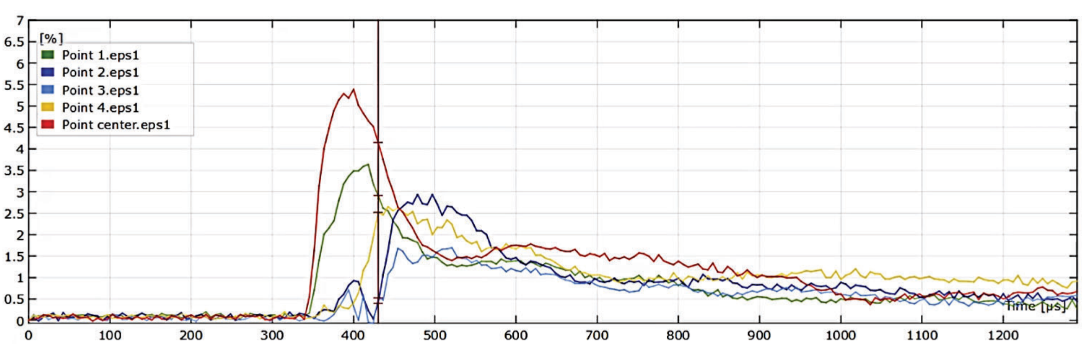

Figure 9. Example of a DIC result: strain history of various points on an aramid backing plate; time scale is microseconds (µs).

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4. DISCUSSION

The REM test method is energy based and as such can be applied to any target material or armour system. Normally difficult to test armour materials like ceramics can be evaluated with this method, but the method could also be used to, for example, quantify the effect of damage or the aging of armour systems. The REM can only be used when the target is overmatched, as this allows the residual energy of the projectile to be determined, together with the status of the residual penetrator (intact, broken, deformed or eroded/shattered).

As an example, in this paper the effect of particle size of the starting powder used to sinter B_4C tiles is demonstrated. All tiles had an areal density of about 25 kg/m^2 and were tested using the same projectile (7.62 AP P80) and the same impact condition. This allows small differences between samples to be determined. The fact that the smallest particle size under-performed, may be explained by the large fraction of grain boundaries in such material. The crystalline order is likely disturbed leading to a large fraction of material with lower mechanical properties (compression strength and hardness).

With Digital Image Correlation in and out of pane deformation of the target rear can be measured (time and space resolved). The accelerations (velocity from zero to maximum) are major, where the highest velocity (240 m/s for the test displayed in Figure 8) is reached directly behind the impact point. Directly after reaching a maximal velocity the velocity reduces again, as more and more backing material is involved in the interaction. The other lines in Figure 8 correspond to the velocity history of positions on the backing further from the impact point. These points start to respond later in time and experience lower accelerations, while their peak velocity and velocity history is practically equal to that of the center point from that moment in time on (red line in Figure 8). This means that the points further away from the centre point adjust to the velocity of the centre point at these later response times. The fact that all moving points axially move at the same velocity, means that the shape of the dent is constant.

From the velocity history plot (Figure 8) also the acceleration of the local positions of the backing can be obtained. The impact point clearly experiences the highest acceleration as its peak velocity of 240 m/s is reached in about 10 microseconds (10^{-5} s) only. Points further away also experience large accelerations but have a lower peak velocity and reach that in a longer time frame. Hence, the axial acceleration is very high, yet decreases with increasing distance to the impact point.

Figure 9 shows the strain history plot of several points on the backing material. Also here, the peak strain value (5.5%) is obtained at the impact point (indicated in the graph as 'center point'). While points further away (points with higher number are further away from the center point), react somewhat later and experience ever lower peak strain values. Also here, the slope of the strain history graphs decreases with distance to the impact point, meaning that the strain rates are reducing with distance from the point of impact. The strain rate at the impact point is about 2700/s (4% in 15 microsecond), while that of point 4 is 1000/s (2.5% in 25 microsecond).

The DIC test method allows the determination of space and time resolved parameters. This can be used to validate FEM simulations and helps the researchers and engineers to understand and quantify the mechanisms involved in the projectile-target interaction. When the main deformation and failure mechanisms are identified and understood, we are in a better position to develop and fine tune materials and systems with better performance. Also, the REM test method proves to be valuable as it allows the quantification of the energy absorbed by (any) projectile-target interaction in which the target is perforated. Although no specific material properties are determined, the energy loss quantification forms a good starting point to understand the (main) mechanisms involved.

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5. CONCLUSION

We performed ballistic tests using 7.62 AP bullets on bare ceramic tiles and ceramic based armour using a set-up that combines the residual energy method with digital image correlation (REM/DIC). Using this combined experimental set-up, useful results are obtained at each shot using any armour system. Shots that perforate the target can be used to calculate the energy lost by the projectile using the REM. Shots that are stopped by the target generate useful data from the DIC set-up; as the rear of the backing material remains largely intact, the speckle pattern remains available for recording by the two high-speed video cameras. This non-contact measuring method allows material behaviour to be measured during realistic impact conditions. High-speed DIC also provides measurements over a wide area with a high time resolution, this allows the important parameters to be determined both time and space resolved.

For the REM a new residual projectile fragment catching device was designed, built and used. It collects the residual projectile after each shot. This allows the residual projectile status and energy loss to be determined. It provides information on the projectile / target interaction process. Using a magnetic filter and an industrial vacuum cleaner, a cycle time of less than 10 minutes between shots was obtained.

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