V_{50} determination challenges for state-of-the-art body armour

M.J. van der Jagt-Deutekom and J.P.F. Broos

TNO, Ypenburgse Boslaan 2, The Hague, The Netherlands
marjolein.vanderjagt@tno.nl

Abstract. The material constructions in personal protective equipment (PPE) have shifted over the last decades. In soft armour ballistics the construction shifted from plain wave fabrics towards more use of Unidirectional (UD) sheets. Also, the use of Ultra High Molecular Weight Polyethylene (UHMWPE) fabric constructions increased significantly compared to aramid. Most state-of-the-art combat helmets are currently constructed from UHMWPE UD composite. All these changes were made to achieve weight reduction and increased ballistic protection for body armour equipment. The ballistic limit velocity (V_{50}) is widely used as a measure of the ballistic performance of a ballistic protective material or construction. This measure does depend on the standard or method used to determine the V_{50}. Four different standards for V_{50} determinations are discussed and compared to show that the ballistic limit velocity of a material is dependent on the test procedure, test requirement and the statistical analysis method used even if the threat, the mounting of the sample and the sample size were the same. Several challenges to accurately determine a V_{50} value have already been reported, such as the effect of start velocity and total number of shots. This paper focusses on effects observed due to the increasing ballistic performance: deformation of the rigid fragment simulating projectile, larger affected impact zone, and increasing Zone of Mixed Results (ZMR). Experimental data is given to support the effects. For all observed effects, solutions are proposed like using a hardened FSP and specifying a minimum shot-to-shot distance. The consequences of these challenges are discussed, including experimental challenges if high V_{50} values must be determined. It is questioned if the V50 value is always the consistent and reliable evaluation parameter to be used, especially when a large ZMR is observed. A solution could be, not to use the V_{50} value as a measure, but instead the percentage of perforations for one or a few specified velocities.

1. INTRODUCTION

The ballistic limit velocity is widely used as a measure of the ballistic performance of a ballistic protective material or construction. This is typically referred to as the V_{50} velocity, which is defined as the velocity for which the probability of perforation, or complete penetration (CP), of the sample by the chosen projectile is exactly 50%. This also means that the probability of the projectile being stopped by the armour, or a partial penetration (PP), will be 50%. The V_{50} is thus a statistical estimation of the ballistic performance of an armour.

While the definition of the V_{50} appears simple, the terminal ballistic event behind it is not. Terminal ballistics is about the behaviour and effects of a projectile when it hits and transfers its energy to a target. This is a complex interaction process. The interaction process depends on the armour and projectile construction and their material properties – quasi-static and dynamic. These determine the failure mechanism of the projectile and armour, such as ductile failure modes, shear failure modes and brittle failure modes. The failure mechanism of the projectile and armour material can differ from each other. The interaction process is also dependent on the striking velocity of the projectile. Assuming one main failure mechanism between a specific projectile – armour combination, the effect of the velocity can be illustrated with figure 1.

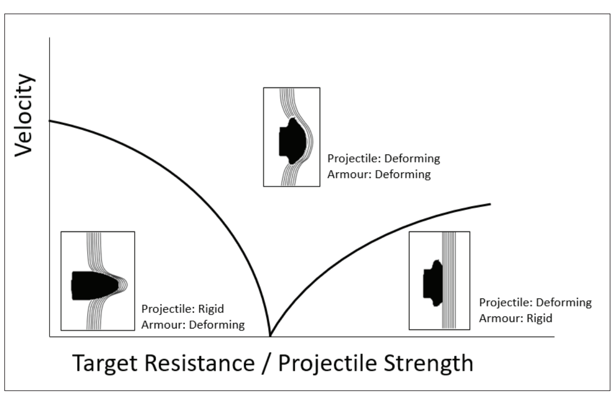

Figure 1. Regions of projectile and target failure mechanisms

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Although the diagram in figure 1 has been derived to model long rod penetrator impact on metallic armour [1], it is illustrative to show the dependence between the striking velocity and the ratio between the target resistance and projectile strength. When the strength of the projectile material is much larger than the target resistance, the projectile remains rigid during the penetration process. For example, when a Fragment Simulating Projectile (FSP) impacts on a soft armour. When the target resistance is much higher than the projectile strength, the armour shows a rigid behaviour while the projectile deforms during the penetration process. The probability that both the target and the projectile deform during the impact and penetration process increases with increasing impact velocity.

The V_{50} value of an armour material is determined for different reasons. In the development stage it is to compare with competitive armour materials or with the minimum requirement. For acceptance testing it is used to check if the ballistic performance complies with the program of requirements. For lifespan control, the ballistic performance of used armour should be randomly checked to see if it still complies with the requirement. It can then also be used to compare the ballistic performance of the new and used armour. A significant decrease in V_{50} value is seen as a degradation of the ballistic performance. For all these evaluations, the V_{50} value must be determined consistently and reliably.

The material constructions in personal protective equipment (PPE) have shifted over the last decades. In soft armour ballistics the construction shifted from plain weave fabrics towards more use of Unidirectional (UD) sheets. Also, the use of Ultra High Molecular Weight Polyethylene (UHMWPE) fabric constructions increased significantly compared to aramid. Most of the state-of-the-art combat helmets are currently constructed from UHMWPE UD composite. All these changes were made to achieve weight reduction and increased ballistic protection for body armour equipment. Due to the increase in ballistic protection, the impact velocities needed to determine the V_{50} have also increased significantly.

The V_{50} is a measure of the ballistic resistance of an armour and is determined by performing a statistical analysis on the gathered ballistic data after a test. For a V_{50} determination, each result should be independent. This implies that in the tested velocity range, the armour material and the projectile should remain constant. That means not deform or deform in the same manner for the whole velocity range. It also means that if multiple shots are performed on the same sample, the distance between shots should be sufficient so that the armour at the next impact location behaves as if it was the first impact.

The procedure to determine a V_{50} value is described in several ballistic standards. All these standards give regulations on the experimental method and the V_{50} calculation method. These methods have all in common that the velocity varies around the zone that results in PP and CP and it is done for the perpendicular impact condition (0°NATO). However, these standards differ in the experimental assessment and in the statistical calculation method.

It is questioned if the V_{50} value is always the consistent and reliable evaluation parameter for all lightweight ballistic protection products, due to the challenges of the increased ballistic performance. This does depend on the standard or method used to determine the V_{50}. Therefore, first a summary of four different standards for V_{50} determinations are discussed and compared, before discussing the effects observed due to the increasing ballistic performance.

2. STANDARDS FOR V_{50} VALUE ESTIMATIONS

The NATO standard for the evaluation and classification of personal armour (STANAG 2920) [2] and the USA Department of Defense test method for V_{50} assessment (MIL-STD-662F) [3] both use the up-and-down firing method for the data acquisition for the V_{50} determination. This method is meant to converge to the average value with a limited number of shots. The V_{50} is calculated as the average of an equal number of highest PP velocities and the lowest CP velocities which occur within a specified velocity spread. The maximum allowable velocity span is dependent on the armour material and test conditions.

The Allied Engineering Publication (AEP), the underlying technical description of the STANAG2920, prescribes that the first round shall be loaded with an amount of propellant to give the projectile a velocity equivalent to the estimated V_{50} ballistic limit of the armour. MIL-STD-662F distinguishes between acceptance testing and other types of ballistics tests. For acceptance testing, the first round shall be loaded with a reference propellant charge so that the striking velocity is 23 to 30 m/s above the minimum required V_{50} as given by the appropriate specification. For other types of ballistics tests, it is the same as AEP-2920. So, for most ballistic tests, the starting velocity depends heavily on the given input before the execution of the ballistic test.

It has been shown previously that these established methods can be open to bias for some types of armour, like body armour, due to the chosen starting velocity and total number of shots [4]. Riley [4] concluded that the uncertainty in the estimated V_{50} will remain large when only a small number of test shots are used. Based on their results, 48 to 60 shots are necessary to reduce uncertainty. Both AEP-2920 and MIL-STD-662F use a lot less shots: respectively 6 to 14 and 4 to 10 depending on the bracket in which all velocities fall.

The methods described above only gives a V_{50} estimate. It is not able to determine a variance for the determination of any penetration probabilities. The AEP-2920 therefore recommends that an indication of the extent of the variability for a particular projectile and target material is given in the final report. For this, further impacts may be used after the first set of fair impacts that meets the criteria for the average V_{50} calculation. According to AEP-2920, firing shall continue until the three conditions mentioned below are fulfilled and the width of 95% confidence interval of the V_{50} is less than 4%:

- the highest velocity shall result in a CP,
- the smallest velocity shall result in a PP,
- there is a ZMR, which means that the lowest velocity producing a complete penetration shall be lower than the highest velocity producing a partial penetration is required.

The AEP-2920 mentions that a maximum of fourteen valid shots should be obtained to compute the V_{50} and standard deviation by means of the Probit method. The method does not give an indication what to do if not all the conditions are met after fourteen valid shots.

The standard of the Association of Test Laboratories for Attack Resistant Materials and Construction (VPAM) [5, 6] and Home Office [7] both describe a procedure and requirements for the V_{50} and the standard deviation calculation for bullet impact. However, the way they define it is quite different.

The VPAM APR2006 [5] does not prescribe a specific firing method or a starting velocity. It is assumed that the probability of penetration is a continuous, normal function of the impact velocity, based on the method from Kneubuhl [8] (KNB). The VPAM-KNB method replaces the probability function by the relative frequency. So, a classification of velocities in specific class ranges must be carried out (e.g. 5 or 10 m/s). From the results of a test firing, three areas can be identified: 1 - with only PP results, 2 – with PP and CP result (ZMR), and 3 – with only CP results. The firing is continued until it meets all the specified conditions:

- The minimal number of shots should be 16 (better 20 to 30)
- Every area must include at least 2 shots.
- Between two neighbouring partitions there can't be more than one empty class of velocity.

Given de minimal number of shots required, more than one PPE sample will be needed for one V_{50} determination. It is the authors experience that the VPAM-KNB method has a bias when the CP/PP ratio deviates significantly from 1. The V_{50} estimate is higher when the CP/PP ratio is low; based on significantly more PP results than CP results.

The Home Office body armour [7] standard uses Critical Perforation Analysis (CPA) software for the assessment of the velocity associated to a given statistical probability of body armour perforation. A minimum of 30 shots shall be performed with the test end conditions governed by the point at which the standard deviation of the V_{50} is below 10% of the mean. This condition shall be indicated by the CPA software. The advantage of this software is that it diminishes the influence of the operator. The software indicates which velocity should be used for each shot.

Helliker [9] gives more insight in the CPA method, which he used for the V_{50} determination against fragments. It is a tool using a Probit statistical analysis. Helliker mentions that the recommended number of shots is a minimum of 40 for fabric armour. The trial is divided into two phases of 12 and 28 shots, respectively. The first phase is a sighting phase to identify the "zone of mixed results" and to provide reassurance that the testing is in the area of interest. At the end of phase 1 a Probit model is fitted to the data from the first twelve shots. This model is used to estimate the V1, V20, V80 and V99 for the current data. The shots in the second phase are divided into seven sets of four shots. The velocities for each set are calculated per set of four.

The VPAM-KNB method and the CPA method specify the velocity at which 1% of shots are predicted to perforate the armour being tested, V_1, as well as the velocity at which 50% of shots are predicted to perforate the armour being tested, V_{50}. Main advantages of the CPA method are that it tries to capture the whole ZMR and that it limits the choices for the operator.

Besides the differences mentioned above, the different standards also prescribe minimal distances. Table 1 shows differences in the minimal distances between shots and from the edge. VPAM-APR does mention that the hits on the test specimen must be chosen in a way that there are no prior damages of previous shots around the point of impact, which could influence the result. VPAM-APR also mentions

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that if the damage of the test specimen is too severe because of too many hits, the test must be continued using a further test specimen. MIL-STD-662F does specify a distance of at least two projectile diameters from any previous impact or disturbed area resulting from an impact. This all is very relative and susceptible on the judgement of the operator.

Table 1. Overview of requirements for distances mentioned in standards for body armour

	MIL-STD-662F [3]	**AEP-2920 [2]**	**VPAM BSW [6]**	**Home Office body armour standard [7]**
Minimal distance from edge	≥2 x projectile diameter	25 mm (50 mm from corner)	30 mm (75 mm from corner)	50 mm
Spacing between shots	≥2 x projectile diameter	≥ 65 mm or ≥10 x projectile diameter	≥ 75 mm	≥ 75 mm: undeformed panels

The ballistic limit velocity of a material depends on the test procedure, test requirement and the statistical analysis method used even if the threat, the mounting of the sample and the sample size were the same. Several challenges to accurately determine a V_{50} value have already been reported, such as the effect of start velocity and total number of shots. This paper focusses on the effects observed due to the increasing ballistic performance; deformation of the 1.1 g FSP fragment simulating projectiles, larger affected impact zone, increasing ZMR, and experimental challenges if high V_{50} values are to be determined.

3. DEFORMATION GAP

Modern fragment protective body armour is tested using fragment simulating projectiles (FSPs), not real fragments. The AEP-2920 standard defines chisel nosed FSPs (CN FSPs) as they provide repeatability, consistency, standardization and allow comparisons among armours. Previous work of Cant [10] shows no linear correlation between real fragments from a 81mm mortar shell and CN FSPs. As expected, CN FSPs behaved in a predictable manner, but did not accurately represent real fragments which behaved unpredictably due to the different shapes, sizes, and masses.

Due to the increase of ballistic protection, the impact velocities needed to determine the V_{50} are significantly increased. During ballistic limit testing of UHMWPE helmets against the 1.1 g FSP threat, the velocity increase is to such an extent that the 1.1 g CN FSP starts to deform at some point during the penetration process. This could mean that the interaction process changes within the ballistic limit velocity range, as illustrated in figure 2. At relatively high velocities the FSP deforms during the penetration process, creating a larger contact surface with the composite materials thereby engaging more fibres and thus becomes easier to arrest. At lower velocities, the FSP could however defeat the armour (complete penetration) because the impact energy is insufficient to deform the projectile. This could be quantified as a deformation-gap like the known shatter-gap phenomena. As described by AEP-2920, shatter gap can result in projectile/armour combinations having multiple ballistic limit (V_{50}) values. This is illustrated in figure 2 for the deformation-gap phenomenon as observed for FSP impact on UHMWPE composite helmets.

For three different UHMWPE helmets, FSPs were recovered after the test for a range of impact velocities. Figure 3 illustrates some recovered 1.1 g FSPs from one UHMWPE helmet shell for different ascending impact velocities. Two dimensions were measured: length and the maximum diameter of the chisel nose (see figure 4). Figure 5 shows the measured dimensions. It shows that the FSP starts to deform around an impact velocity of 550 m/s and that the amount of deformation not only depends on the impact velocity but also on the specific helmet shell construction.

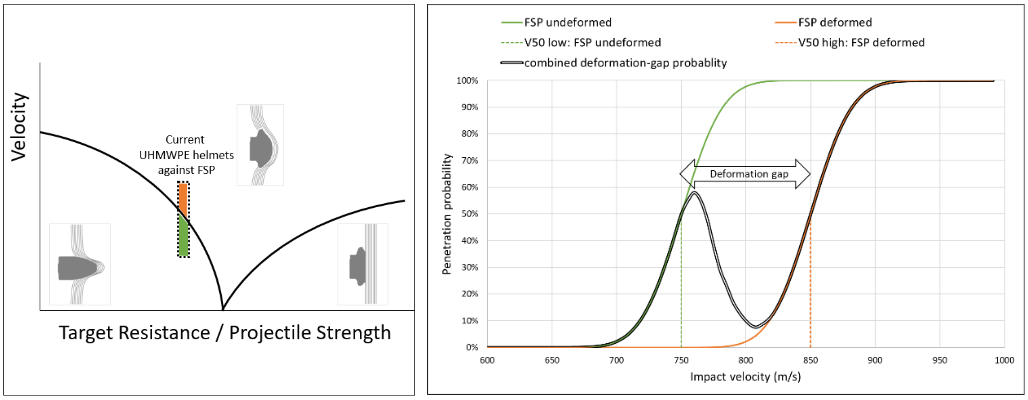

Figure 2. Schematic illustration of the deformation-gap phenomenon.
Left: Interaction process changes within ballistic limit velocity range.
Right: Example of the deformation perforation probability distribution of a deformed FSP V_{50}, undeformed FSP V_{50} and combined.

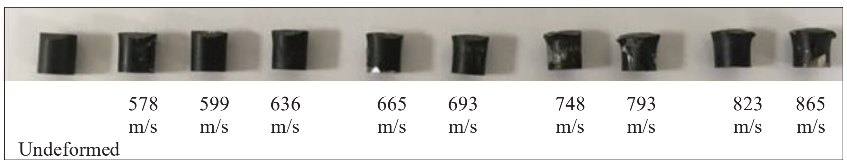

Figure 3. Illustration of the standard 1.1 g FSP recovered from a UHMWPE helmet shell with their corresponding impact velocities

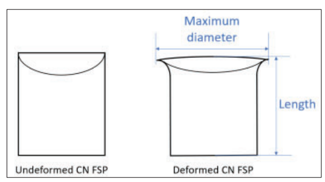

Figure 4. Schematic illustration of the two dimensions measured of the deformed FSP

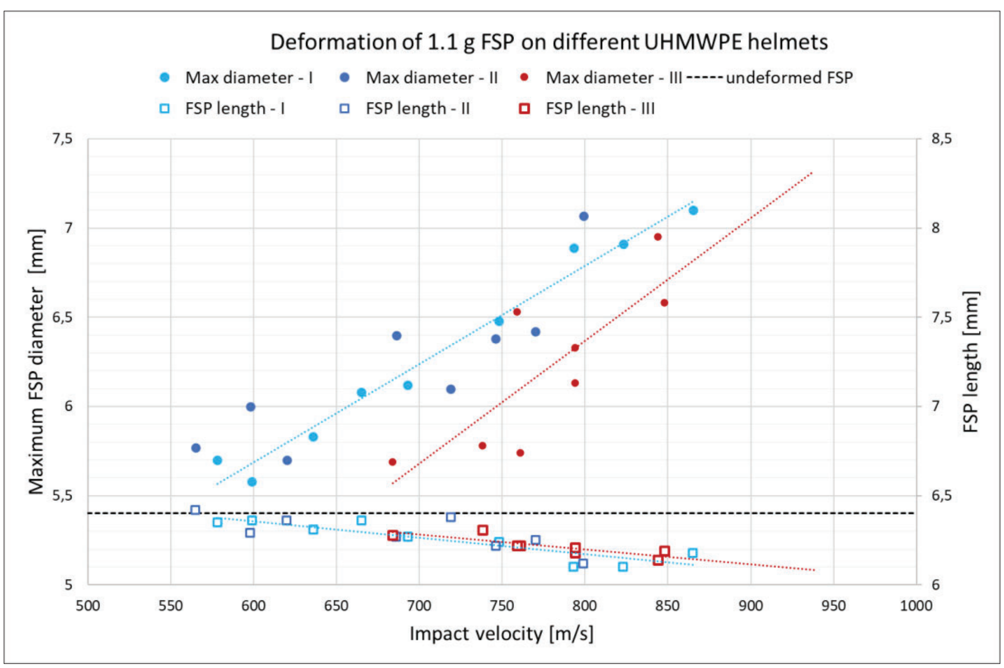

Figure 5. Dimensions of recovered FSP from three different UHMWPE helmets: I, II and III indicate from which helmet shell it was recovered

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As mentioned before, the chisel nosed FSP's are defined to provide for repeatable and consistent comparisons between protective armour materials. It can be questioned if the current hardness of the FSP is still suitable for determining these increasing V_{50} results. The standard CN FSP has a hardness of 30 HRC. To explore the effect of the FSP hardness, V_{50} tests have been done with a hardened CN-FSP of 60 HRC. In these experiments the velocity was varied along the ZMR to strive to cover the whole ZMR. The V_{50} was estimated with the Probit method of AEP-2920. The data points and the Probit curves for both FSP types are given in figure 6. The two-coloured areas indicate the ZMR for the two FSP types. The partial penetrated hardened FSPs were recovered from the helmet shell (see figure 7) and showed no deformation for the whole velocity range tested. For the hardened FSP, the V_{50} decreases with 86 m/s compared to the standard FSP. The ZMR was comparable with standard FSP. This shows that the large ZMR is not only caused due to the deformation-gap, but also due to the inhomogeneity of the helmet shell.

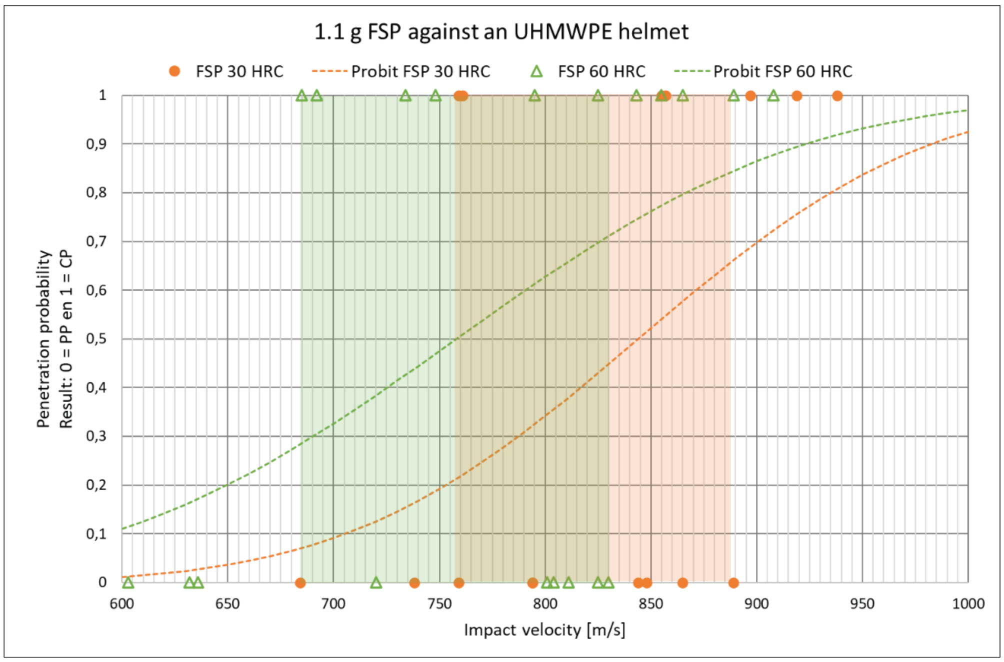

Figure 6. Penetration probability for the standard 1.1 g FSP of 30HRC and hardened to 60 HRC of a UHMWPE helmet: individual results and calculated Probit curve

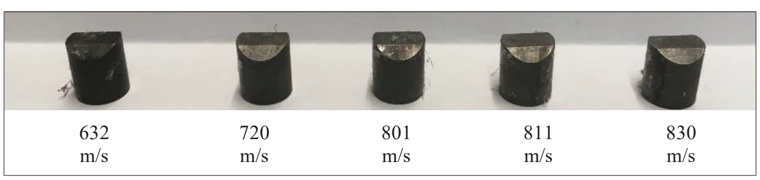

Figure 7. Illustration of the hardened 1.1 g FSP of 60 HRC recovered from a UHMWPE helmet shell for different impact velocities

Deformation gap can also be an issue for deforming bullets. When the V50 is determined in the velocity range where the bullet significantly deforms, it is likely to overlook the low velocity penetration probability of the undeformed bullet. This is also important to realize for V_{proof} classification of personal armour. In these tests the velocity remains constant, mostly around the muzzle velocity for the specific projectile. Such a test must ensure that at a confidence level of 90%, the probability of a partial penetration for the specified projectile at the velocity specified (V_{proof}) is higher than 90%.

4. SHOT SPACING

V_{50} testing standards assume that all impacts are independent. The hits on the test specimen must be chosen in such a way that there are no prior damages of previous shots around the point of impact, which could influence the result. It has been shown previously that these established V_{50} methods can be open to bias for body armour, due to the chosen starting velocity [4], total number of shots, and to the result of the previous shots on the test specimen [11]. Schaap [11] proposes an alternative test sequence by testing one velocity per panel to decouple the influence of stop-perforation history and bullet velocity. However, it is therefore important to consider the shot spacing.

In V_{50} testing of fabrics and composites, multiple shots are fired on a single piece of armour, while using a shot pattern that prevents hitting the same fibre twice. It is often implicitly assumed that by taking these precautions, individual shots in a V_{50} test do not affect the ballistic resistance of later shots and each shot can be regarded as independent. Analyses by van Es [12] of shot data with 9 mm FMJ DM41 on hard composite panels of Dyneema® HB26A showed that individual shots in the V_{50} test are not independent. The ballistic resistance of this material improves during a V_{50} test: The V_{50} of the third shot is higher than for the first shot. This was all done for one shot pattern of 8 shots per panel. Van Es concluded that it is recommended to limit the number of shots on a panel such that the ballistic resistance of the panel is not changed because of testing.

The effect of shot-to-shot distance and the effect of number of shots have been investigated with the 9 mm DM41 projectile against a hybrid soft armour of UHMWPE-UD and an aramid plain weave. A maximum of 6 shots per panel were performed with alternating multi hit pattern (based on VPAM-BSW pattern): the first 3 shots within a large equilateral triangle (150 mm) and the second 3 shots within a small equilateral triangle (75 mm) configuration as shown in figure 8 top left. Tests were done on 12 panels in total. The first 7 panels were tested with a constant velocity as recommended by Schaap [11] to scan for the whole ZMR. This was done in the velocity range 480 to 560 m/s with steps of 20 m/s. The results of the first five impact velocities are shown in figure 8. The two highest velocities resulted in CP on all six impact locations. Additional shots on the other 5 panels were with varying velocity to determine a Probit V_{50} per shot location. Figure 9 shows the Probit V_{50} for each shot and the Probit V_{50} for the two-triangle configuration. This shows that the V_{50} increases for the smaller shot-to-shot distance. A shot-to-shot distance of 75 mm is too small for the 9 mm threat; the material damage due to the previous shot does influence the subsequent shot and is thus not independent.

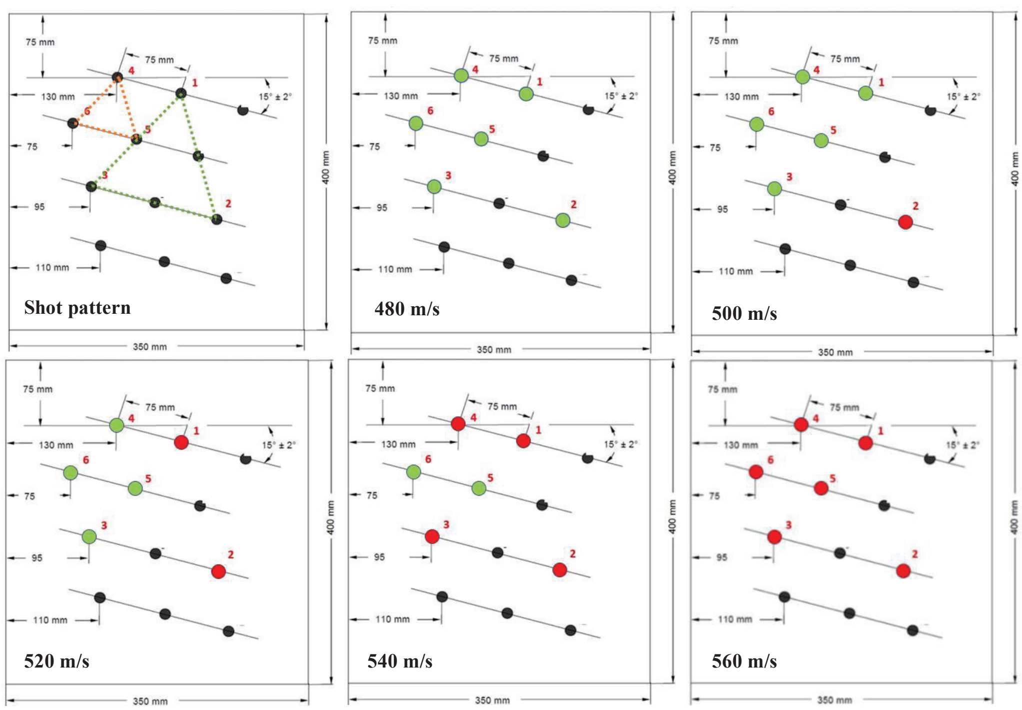

Figure 8. Schematic display of the hybrid soft armour after 9 mm DM41 impacts. Results for five different impact velocities per sample. Red dot = CP, green dot = PP. Top left: shot pattern.

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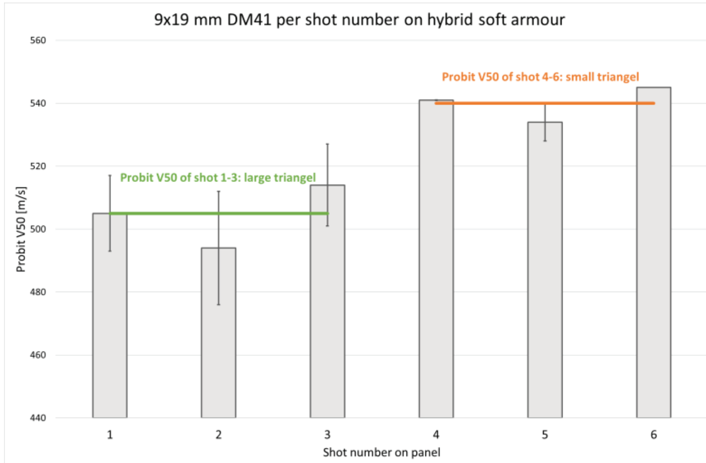

Figure 9. V_{50} results of 9 mm DM41 on hybrid soft armour with alternate shot pattern

5. DISCUSSION

The improvements in the material constructions in PPE resulted in thinner and lighter products with an increased ballistic protection. As discussed previously this can result in more projectile deformation and a larger affected impact zone. This all increases the complexity of the interaction process, which influences the ZMR. As illustrated in figure 10 the complexity increases when the projectile deforms during the penetration process and when the inhomogeneity of the armour material construction increases.

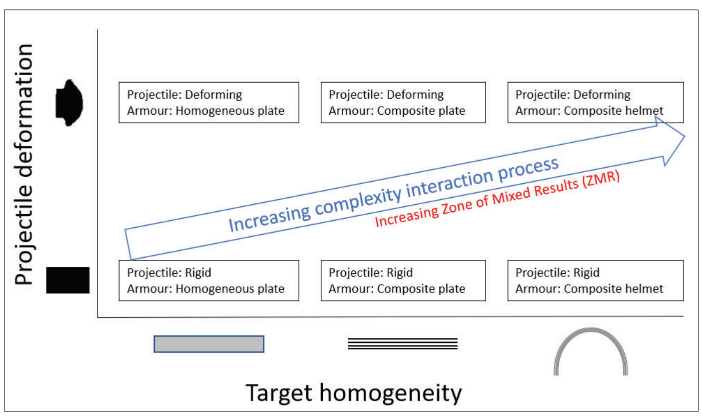

Figure 10. Illustration of the increasing complexity of the projectile target interaction process

A homogeneous hard armour with consistent thickness and material properties impacted by a non-deforming projectile usually has a small ZMR. This means that the probability of the projectile perforating the armour at a velocity slightly less than the V_{50} can be negligible. For soft armour panels and flat composite plates, the ZMR is a significant zone to be accounted for. This means that there is still a probability of the projectile perforating the armour at a velocity more than 50 m/s below the V_{50} [4]. The ZMR for UHMWPE helmets is much larger; there is still a probability of the projectile perforating the armour at a velocity more than 100 m/s below the V_{50}. For the current helmet testing this is partly due to deformation gap, but even with a hardened non deforming FSP, the ZMR is still significantly large with around 150 m/s (see figure 6).

Several factors contribute to the inhomogeneity of the helmet shell. The helmet shell varies around the surface in curvature, thickness, and laminate structure. In addition, there is also the variation in the applied production process, such as compression pressure and temperature and their distribution over the helmet shell. This would advocate to determine the ballistic performance of a helmet with a "one velocity" per helmet as previously proposed for hard composite plates [11] and soft armour panels [13]. For composite plates and soft armours, it is to account for the effect of the shot results. For the helmets, it is needed to account for the different ballistic performance over the shell surface. It can be questioned

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if the V_{50} value is a representative value for helmets for assessing the ballistic performance, because it is clearly an average value for the whole shell.

If the V_{50} value is nevertheless desired, it is preferred to use a method least sensitive to the known bias factors and which covers the whole ZMR, like the proposed ballistic limit approach of Mauzac [13]:

- one-velocity-per-sample.
- velocities from approximately 0% to 100% CP.
- minimum of 6 test specimens per V_{50} (add more specimens if more velocities are needed).
- Probit method with confidence interval.
- In addition to [13], it is preferable to do the testing with an FSP with a hardness of 60 HRC to eliminate the effect of the deforming FSP.

A problem could be the substantial number of shots needed for statistical significance and accuracy of the test results. For soft armour this could be solved by optimizing the shot placement and order [13]. It should be investigated if and how this could be applicable for a helmet shell.

However, another problem will be the high velocities needed to achieve about 100% CP with the standard fragments. For the current fragment protective helmets, this means impact velocities of at least 1000 m/s are needed. Rifle helmets on the market already specify V_{50} values of more than 1000 m/s against the 1.1 g FSP. This means that impact velocities of at least 1400 – 1500 m/s are needed to achieve around 100% CP. These high impact velocities are experimentally possible, but it requires more sophisticated equipment than for "standard" V_{50} testing. At these high velocities more experimental variation will also occur with an FSP, like a larger absolute velocity variation and larger yaw. This all decreases the accuracy of the test results.

The problem of the high velocities could be mitigated by not using the V_{50} as a requirement or a measure, but by using the percentage of perforation for one or a few specified velocities. This method should still be based on the one-velocity-per helmet method. Instead of the V_{50} assessment, this method would focus more on the lower boundary of the ballistic limit, which is more relevant from a survivability point of view. Instead of a requirement for the V_{50}, a maximum percentage of CPs for the specified velocity/velocities are then given.

The above-mentioned solutions are also applicable for V_{50} determinations with bullets. However, V_{50} determinations with bullets are mostly done with impact velocities higher than the actual muzzle velocity, which gives even more restrictions. First, the number of independent impacts possible on a sample will decrease if the V_{50} increases. Second, for the penetration process to be comparable to the operational velocities, the bullet deformation during impact should not change significantly. When using higher velocities than normally used, it should also be considered that the bullet shape does not change during acceleration and flight. This requires expertise on internal and intermediate ballistics, to make sure it behaves the same as under normal operations. This could be achieved with an adjusted barrel and powder. Still, it is recommended that the bullet shape is checked with high-speed imaging before impact. In the effort to better define the V_{50}, the process around it is becoming increasingly complex.

6. SUMMARY

Nowadays, PPE equipment is thinner and lighter with increased V_{50} values. Even if the threat, the mounting of the sample and the sample size were the same, the V_{50} value is dependent on how it has been determined. Thus, dependent on the test procedure, test requirement, operator and the statistical analysis method used.

The increasing ballistic performance could result in more projectile deformation and a larger affected impact zone, which also affects the V_{50} determination. The increasing V_{50} values for helmets show the possibility of a deformation gap with the standard FSP. For velocities higher than 550 m/s, the 1.1 g FSP is staring to deform. Using hardened FSP's with 60 HRC could be a solution to eliminate the deformation gap observed for UHMWPE helmets. For 9 mm ball projectiles it is shown that the shot-to-shot distance of 75 mm leads to higher V_{50} values, because the material damage due to the previous shot influenced the subsequent shot and is therefore not independent.

The increasing complexity of the interaction process also increases the ZMR. For PPE with large ZMR results, like modern helmets, it is advised to use a one-velocity-per-sample method, because that is least sensitive to the known bias factors. Problem is the large number of shots needed to cover the whole ZMR. A solution could be, not to use the V_{50} value as a measure, but instead the percentage of perforations for one or a few specified velocities.

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