Effect of consolidation pressure on the impact behaviour of AK47 MSC on UHMWPE composite panels

H. van der Werff[1], U. Heisserer[1], J. van Elburg[1], W. Riedel[2]

[1]*Avient Protective Materials (APM), P.O. Box 1163, 6160 BD Geleen, The Netherlands, harm.werffvander@avient.com*
[2]*Fraunhofer Institute for High Speed Dynamics, Ernst-Mach-Institute (EMI), Zermelo Str. 4, D-79104, Freiburg, Germany.*

Abstract. Higher consolidation pressures during hot-pressing of UHMWPE composite panels are known to strongly improve the V_{50} performance, but the exact mechanism of this effect is not fully understood. In this study, the impact behaviour of the AK47 Mild Steel Core (MSC) projectile on four UHMWPE composites, mainly differing in resin type, processed at different consolidation pressures has been investigated in detail by the determination of V_{50}, and by depth-of-penetration and final core deformation measurements over a wide range of impact velocities. The V_{50} increased with higher consolidation pressures for all composite types. At projectile impacts below V_{50} with partial penetrations, increased consolidation pressures reduce the depth-of-penetration and result in higher deformation of the projectile steel core. All four UHMWPE composite types show different characteristic behaviours for V_{50}, depth-of-penetration and core deformation. Comparison of the results with shock wave properties from plate impact testing, suggests that higher consolidation pressures result in reduced porosity, a more homogeneous impact response and higher contact pressures between composite panels and projectile.

1. INTRODUCTION

Composites of high strength ultra-high molecular weight polyethylene fibres (UHWMPE) can be hot-pressed into panels offering high ballistic limit V_{50}'s for various threats at low weights [1]. It is known in practice that higher consolidation pressures during hot-pressing of the panels can lead to strong increases in V_{50} [2], but the exact physical mechanisms causing this behaviour are not fully known. This paper reports experimental results on the effect of panel consolidation pressure on 7.62x39mm AK47 MSC V_{50}, depth-of-penetration and deformation of the mild steel core, to provide more insight into the mechanism of the consolidation pressure effect.

2. EXPERIMENTAL

Experiments were carried out using four different UHMWPE composite types manufactured by Avient Protective Materials (APM) under the brand name Dyneema®: HB212, HB210, HB311 and HB480. All these four UHMWPE composites use the same UHMWPE fibre, but have different resin types. All the sheets of the composite types consist out of four uni-directional fibre layers stacked in a 0°/90° manner. Because of the different resin types, different consolidation temperatures have to be used for the different composites. Details are given in Table 1.

Table 1. Prepreg sheet areal densities of the UHMWPE composites and consolidation temperatures.

UHMWPE composites :	HB212	HB210	HB311	HB480
Areal density (g/m^2)	136	136	129	109
Consolidation temperature (°C)	125	130	130	145

HB212, HB210 and HB311 are conventional UHMWPE fibre composites obtained by impregnating the same fibre with three different resin systems. The resin stiffness increases from HB212 to HB210 and further to HB311. For AK47 MSC impact, higher resin stiffness in conventional UHMWPE fibre composites typically results in lower backface deformation but also slightly lower V_{50}. HB480 is not a conventional UHMWPE fibre composite. It is made using a proprietary manufacturing process (which we refer to as UD Film) and results into very stiff panels (so low backface deformation) but also higher V_{50} when impacted by AK47 MSC and Fragment Simulating Projectiles (FSP).

https://doi.org/10.52202/081621-0003

All panels were produced using an oil-heated hydraulic press with flat platens. 20x20 cm panels were prepared of each composite type varying the consolidation pressures from 20 bar, 165 bar to 300 bar while maintaining a constant areal density.
The thickness of the pressed panels was measured with a digital caliper on nine different locations in the panel.

The 7.62 mm AK47 MSC projectiles (124 gr / 8 g) were manufactured by Sellier & Bellot and fired in a range set-up shown schematically shown in Figure 1. The average Vickers Hardness measured on various locations of two cores was 177 HV10.

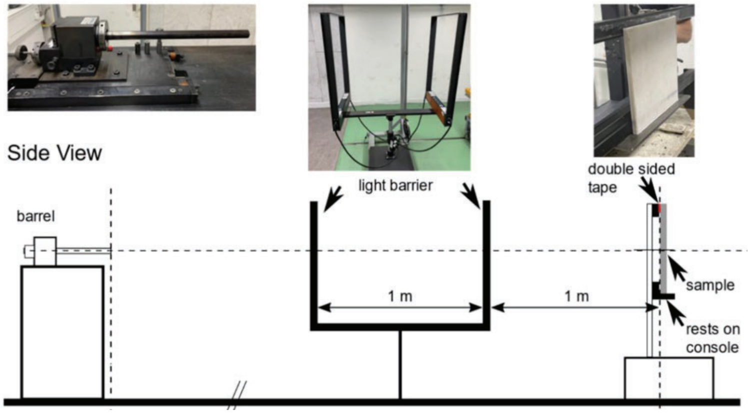


Figure 1. Schematical set-up of the shooting range.

The projectiles were shot from a barrel, adjusting the intended projectile velocities by the amount of powder in the cartridge. The projectile velocity was measured using two light barriers at 1 m distance, placed 1 m in front the target panel. The panel was mounted behind an upper and lower steel bar, maintaining its position by pressing the panel against double-side sticking tape on the bars. The distance from barrel to target was 12 m.

Each panel was shot only once with a projectile aimed at the center. Typically, over 25 samples were tested for each combination of composite type and consolidation pressure over a large range of impact velocities.
In case of a “stop” (i.e. a partial penetration), the panel was sawn open with a band-saw in order to retrieve the mild steel core. The length reduction from initially 20.0 mm was determined with a caliper. In case of a stop, the depth-of-penetration was determined as shown in Figure 2.

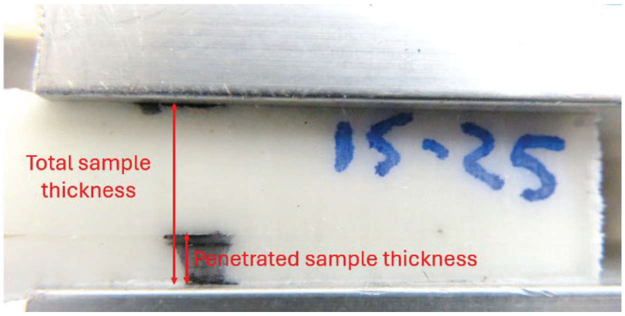


Figure 2. Determination of depth-of-penetration.

Deriving the depth-of-penetration by simply measuring the remaining sample thickness at the point of impact is inaccurate as the extensive shearing of the fibres leads to a thickening of the material. Therefore, the end of the penetrated sample thickness is taken at the point of impact, and this interlayer was tracked with a thin screw-driver towards and marked at the edge. The marked sample was then firmly clamped in an anvil, and the depth-of-penetration was determined as the penetrated fraction of the total sample thickness, as shown in Figure 2.

3. RESULTS

3.1 V_{50} and panel thickness

All individual shots were classified as stops (partial penetrations) or perforations (complete penetrations). The normalised results of the individual shots are shown in Figure 3. The V_{50} was calculated using a Probit analysis (based on the cumulative normal standard deviation).

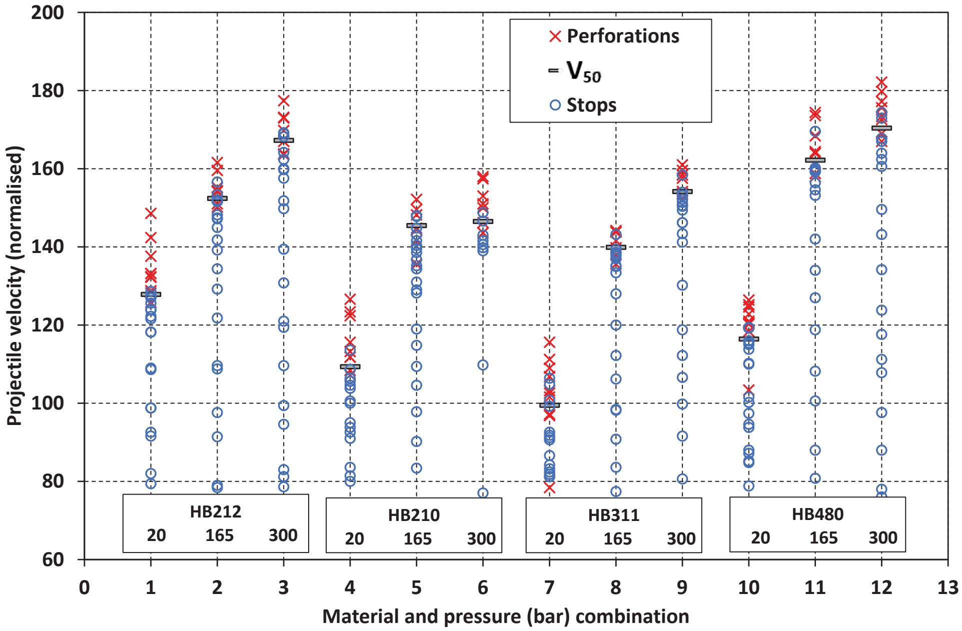


Figure 3. Individual shot result (normalised velocities) for all UHMWPE composite types pressed at the different consolidation pressures (20, 165 and 300 bar).

Figure 3 shows for almost all composites a very small region with mixed results. For the HB311, a low velocity penetration was observed at a normalised projectile velocity of 79, which is noticeably below the V_{50} of about 100. Low velocity penetrations of the AK47 MSC are known in the standards as the so-called shatter gap [3]. The stress that a projectile experiences upon impact is directly related to the impact velocity and the impedances of both projectile and target. If the impact velocity is too low the projectile core can not be deformed and the penetration probability increases.

The V_{50}'s calculated from the data in Figure 3 are plotted versus the consolidation pressure in Figure 4. The dashed lines are guides to the eye. For every composite type, the V_{50} increases very strongly from 20 to 165 bar. From 165 to 300 bar, the further enhancement is much smaller but still present. The results shown in Figure 4 also corroborate that AK47 MSC V_{50} for the conventional fibre UD composites decreases with higher resin stiffness (from HB212 to HB210 to HB311), and that the UD Film composite outperforms the conventional fibre UD composites.

Higher consolidation pressures generally result into significantly lower panel thicknesses. HB311 pressed at 300 bar is the only exception, as it has similar thickness to the panels pressed at 165 bar. This means that indeed voids are present in a panel after consolidation and that the total volume of voids is reduced by increasing consolidation pressures. In [4], defects (such as voids, missing fibres) in pressed UHWMPE panels (pressed only at one consolidation pressure of 206 bar) were clearly identified with micro X-ray computed tomography.
Figure 5 shows that there is no unique relation between panel thickness and V50. At a normalised panel thickness of 98, HB480 achieves a much higher V50 than HB210. The results indicate that the resin properties do significantly contribute to the V_{50} of a consolidated panel.

https://doi.org/10.52202/081621-0003

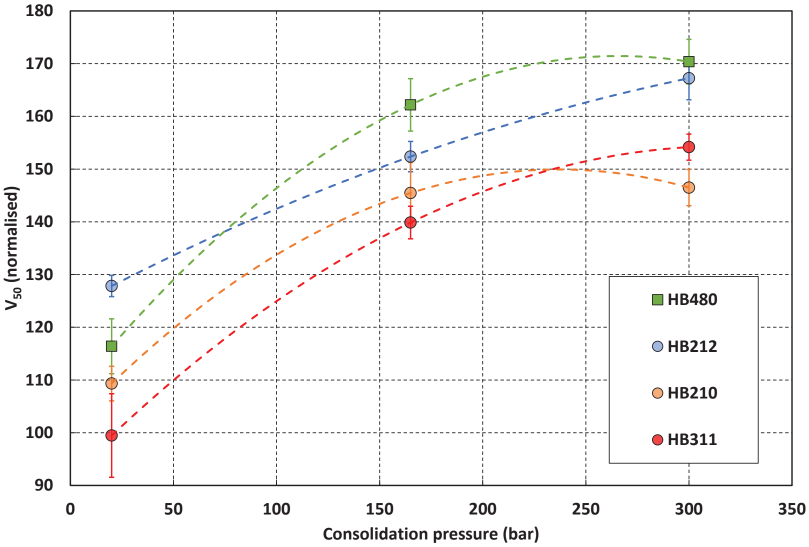


Figure 4. V_{50} versus consolidation pressure (error bars are the 95% confidence intervals).

The V_{50} is plotted versus the sample thickness in Figure 5. The consolidation pressures are given at the data points.

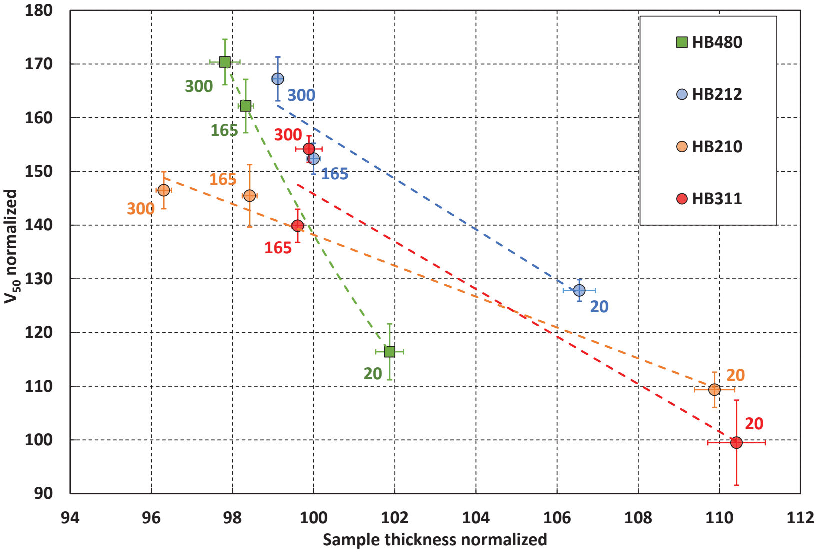


Figure 5. Normalised V_{50} versus normalised sample thickness (error bars are the 95% confidence intervals). The data labels provide the consolidation pressures (bar).

3.2 Core deformation and dept-of-penetration

Of the stopped projectiles, the depth-of-penetration and the residual length of the mild steel core were measured. After impact, the core is typically shortened and has a mushroom-like top [5]. The latter will result into a larger frontal area of the projectile and thus to a reduction of the mass per area of the projectile. It is known that the V_{50} in general scales with the ratio of the areal density of the target over the areal density of the projectile [6]. A higher ratio results in a higher V_{50}.
In Figure 6, the frontal surface area (= π/4 * diameter^2) of a selection of retrieved cores is plotted versus the length of the core.

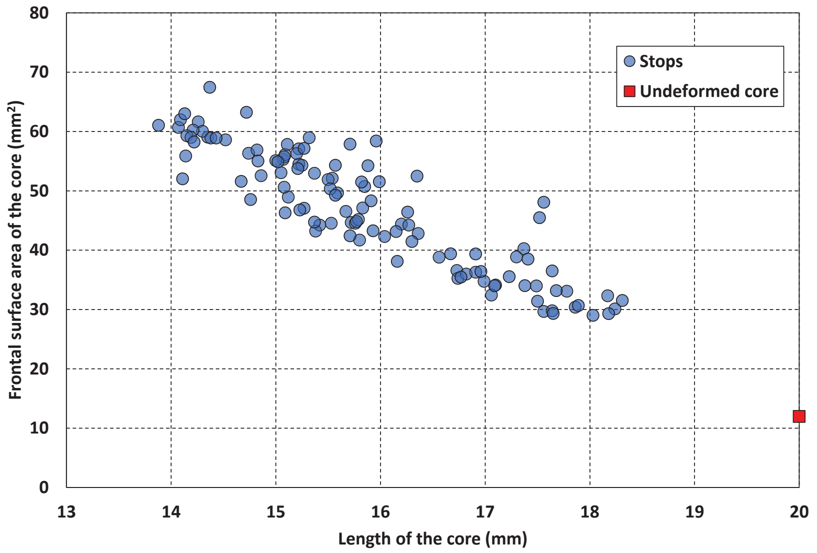
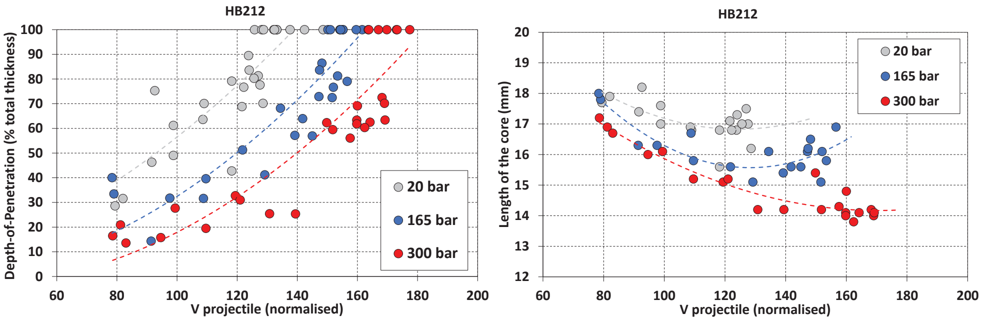


Figure 6. Frontal surface area of retrieved cores (from stops) versus the length of the core.

In Figure 6, the initial frontal surface area and core length of the undeformed core is also plotted. The residual core length clearly relates inversely to the final frontal surface area of the core. During core deformation, the frontal surface area of the cores increases very strongly. Ultimately, at a core length of 14 mm, the frontal surface area of the core has increased five times. Deformation of the core must thus be an important process in stopping the AK47 MSC projectile.

Figure 7 plots for all different UHMWPE composites the depth-of-penetration (left column) and the length of the cores versus the impact velocity (right column). The results demonstrate that an increase in consolidation pressure does lead to a decrease in depth-of-penetration at a given projectile velocity. For example, HB212 pressed at 20 bar, has a depth-of-penetration of almost 60% at a normalised projectile velocity of 100. HB212 pressed at 300 bar has a depth-of-penetration of around only 20% at the same projectile velocity. This is a drastically different response caused by the variation in consolidation pressure. Similar behaviour can be observed for the other composite types, although for HB212 the difference between 165 and 300 bar is most prominent, as can be seen in the left column of Figure 7.
To a lesser extent, the consolidation pressure affects the reduction of the core length. Going from 20 to 165 bar, there is more shortening of the core for all composite types, but less so going from 165 bar to 300 bar.

The data shown in Figure 7 have been rearranged into four graphs of length of the core versus depth-of-penetration per composite type (Figure 8). These graphs show different behaviour of the four composite types. All the graphs in Figure 7 and Figure 8 demonstrate that, at a consolidation pressure of 20 bar, the response of the target, in terms of depth-of-penetration and length of the core, does show more scatter than at the higher consolidation pressures. It indicates that the targets do become more homogeneous at higher consolidation pressures, which can be related to the distribution of resin around the fibre and/or reduction of void content.



https://doi.org/10.52202/081621-0003

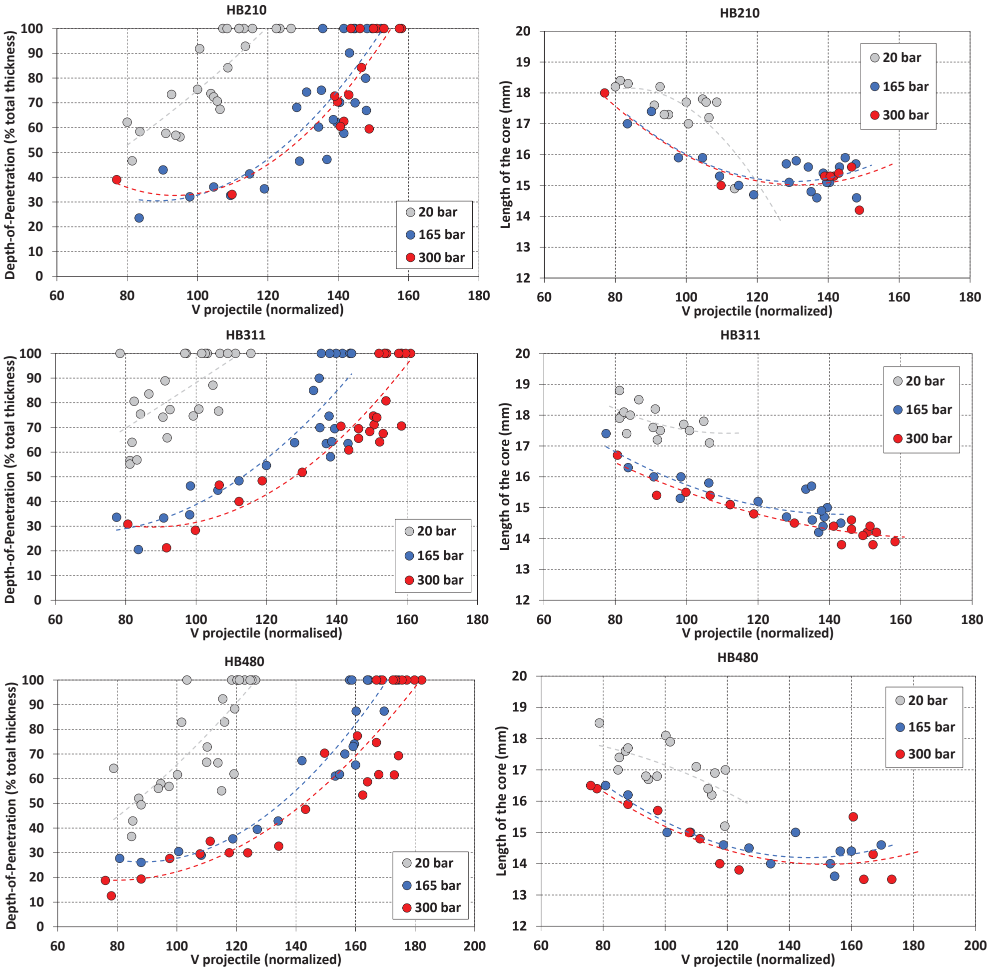
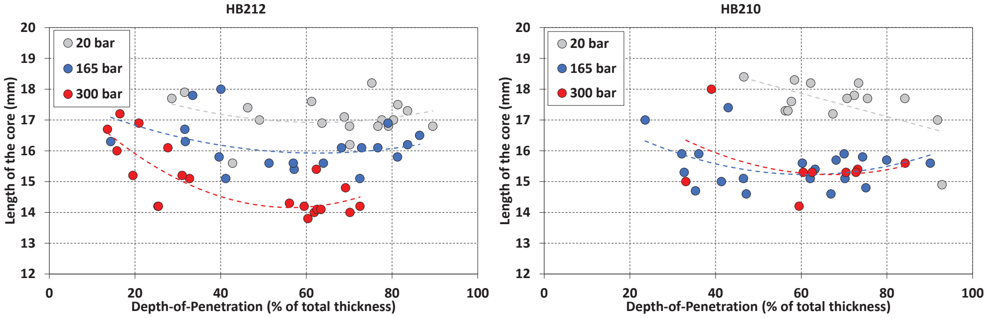


Figure 7. Depth-of-penetration versus projectile velocity (left column) and length of the retrieved mild steel core versus the projectile velocity (right column) for all different UHMWPE composite types.

The above results agree with a previous study [7], where the impact behaviour of an undeformable steel sphere was investigated on Dyneema® HB26 panels consolidated at 20, 165 and 300 bar. The V_{50} increased strongly only going from 20 to 165 bar. Also depth-of-penetration, at a given impact velocity, decreased going from 20 to 165 bar.



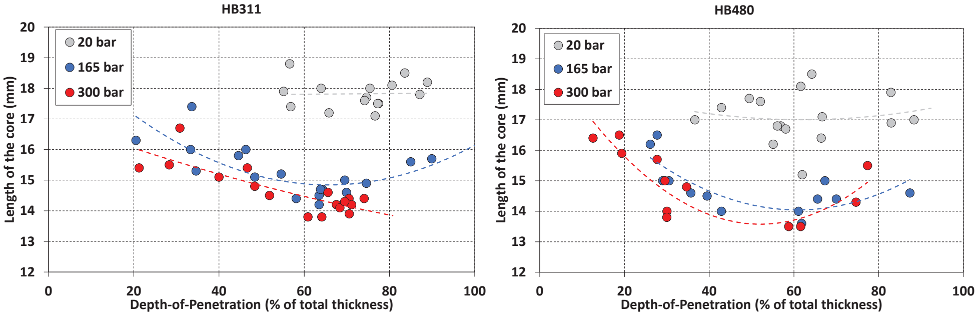


Figure 8. Length of the retrieved mild steel core versus the depth-of-penetration for all different UHMWPE composite types.

3.3 Shock properties

In addition to impact tests with complex three-dimensional stress and strain fields, the shock properties of panels were investigated using planar plate impact experiments as published in [7]. In this test, a UHMWPE sample plate, backed by a 5 mm C45 steel plate, is impacted onto a 5 mm C45 steel target plate leading in the center to a state plane strain. The target surface velocities are recorded with a VISAR laser system during the impact with a resolution of 2 ns. The HB26 data from [8] is given in Figure 9, together with new results measured on an UD Film prototype comparable to the HB480 composite used in this study.

When a projectile impacts on a pressed plate, the resulting pressure P depends directly on the shock properties, as derived from momentum conservation [8]:

$$P = \rho_0 \, U_S \, u_p \qquad (1)$$

with the initial density ρ_0, the through-thickness shock wave speed U_S and material (or "particle") velocity u_p.

Figure 9 shows for HB26 below a particle velocity of 1100 m/s systematically lower shock velocities for a consolidation pressure of 20 bar compared to 165 bar. This difference can be attributed to pores in the panel consolidated at 20 bar. Similar behaviour has been identified for porous concrete and aluminium materials [9]. Going to 300 bar, the shock velocity again increases, at same particle velocities. Figure 9 also shows that the shock properties of a UD Film composite consolidated at 165 bar are even slightly higher that the shock property of HB26 consolidated at 300 bar.

Higher shock velocities in the composite and thus increased pressures on the projectile during impact and deep penetration result in stronger projectile deceleration and core deformation. Increased mushrooming will additionally lead to a larger frontal area with a higher deceleration force on the core. Both processes contribute to and explain the decreased depth-of-penetration, more core deformation and thus higher V_{50} with increasing consolidation pressures, as observed in Figures 7 and 8.

https://doi.org/10.52202/081621-0003

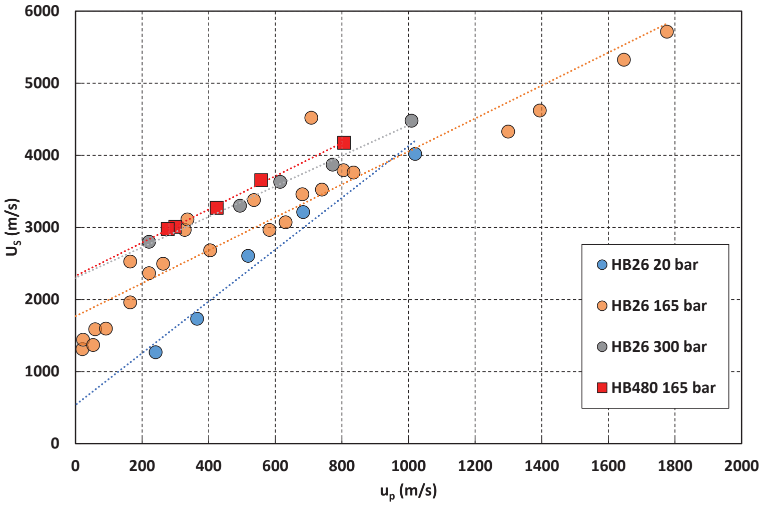


Figure 9. Shock properties under planar impact for HB26 consolidated at 20, 165 and 300 bar [7], and for HB480 consolidated at 165 bar.

3.4 Statistical relations

The obtained data on projectile velocities, depth-of-penetrations, core lengths and V_{50}'s were analyzed in statistical software Minitab® to find good statistical models to predict V_{50}. In Figure 10, the experimental V_{50} is plotted versus the predicted depth-of-penetration at an impact velocity of 100. The latter data were obtained by using a linear model for each composite, at each consolidation pressure. Figure 10 shows that the V_{50} of a composite can be estimated by shooting the projectile at a reference velocity below V_{50} and subsequent measurement of the depth-of-penetration. This can be very interesting if one, in practice, is confronted with an insufficient number of samples for V_{50} determinations. Figure 10 show remarkably that this estimation of V_{50} even works nicely for samples with a V_{50} much higher than the reference velocity of 100. For example, HB480 and HB212 pressed at 300 bars have V_{50}'s close to 170, but nevertheless fall on the general linear fit.

Most strikingly, the simple linear relation in Figure 10 describes very similarly the four different UHMPWE composites with different resins and different fibre compactions, at three different consolidation pressures.

Figure 11 plots the statistically predicted depth-of-penetration versus predicted length of the core, using linear models for both, at an impact velocity of 100.

Figure 11 does show that the different resin systems in conventional UHMWPE fibre composites can have different characteristics. HB311, with the stiffest resin, leads to much more penetration, at a given level of the length of the core, than HB212, with the softest resin. HB480 and HB210 are between of the former two resin systems.

The quality of the linear fits (expressed by the R^2 values) for depth-of-penetration and length of the core with projectile impact velocity are given in Table 2.

Table 2 shows that the quality of the linear fits increases strongly going from 20 to 300 bar consolidation pressures, especially for the depth-of-penetration. This indicates again more defined target response with increasing consolidation pressures. This improved homogeneity can originate from void removal and/or better distribution of the resins around the fibres in the stronger pressed composites.

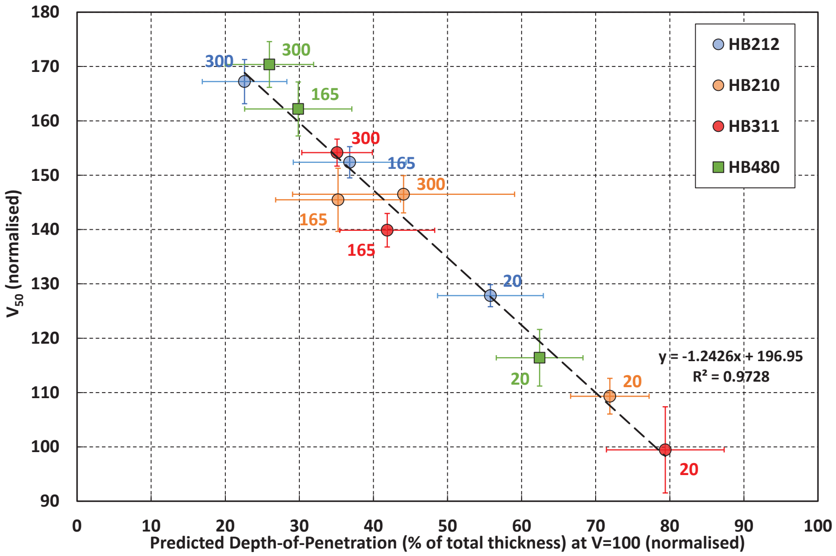


Figure 10. Experimental V_{50} versus predicted depth-of-penetration at V projectile = 100. The error bars are the 95% confidence intervals.

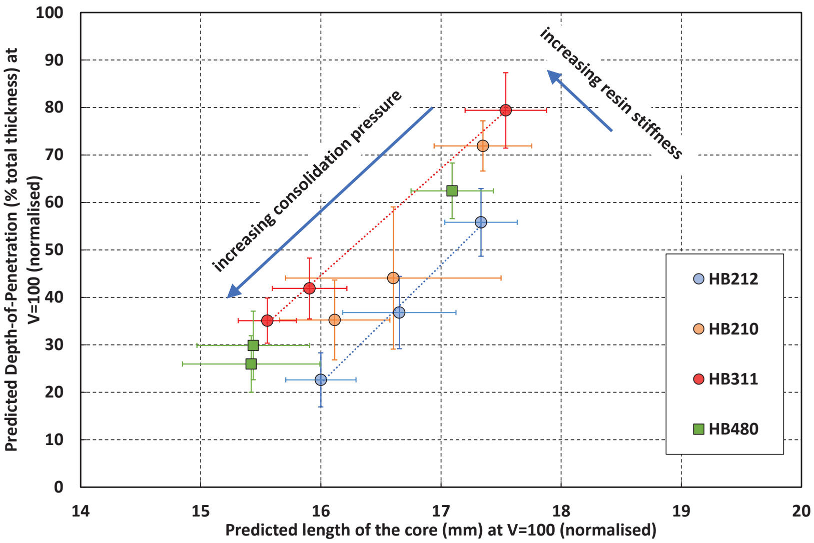


Figure 11. Predicted depth-of-penetration versus predicted length of the core, both at a V projectile = 100. The error bars are the 95% confidence intervals.

Table 2. R^2 of the linear fits per material and consolidation pressure

		R^2 (%) of linear fit with V projectile	
Material	Consolidation pressure (bar)	Depth-of-penetration	Length of the core
HB212	20	61	36
HB212	165	76	34
HB212	300	86	86
HB210	20	56	46
HB210	165	68	40
HB210	300	62	65
HB311	20	30	30
HB311	165	76	70
HB311	300	90	87
HB480	20	46	41
HB480	165	86	63
HB480	300	85	58

https://doi.org/10.52202/081621-0003

4. CONCLUSIONS

The effect of panel consolidation pressures of 20, 165 and 300 bar during hot-pressing on the impact resistance to AK47 MSC projectile has been investigated for four UHMWPE composites.

Higher consolidation pressures result into higher V_{50}'s for all investigated composites, and in decreased thicknesses of the pressed panels. For all composites, the depth-of-penetration at a given projectile velocity decreases strongly with higher consolidation pressure, with the strongest effect between 20 and 165 bar. In addition, increasing consolidation pressures lead consistently to stronger shortening and mushrooming of the mild steel core. In general, both relations show slightly different behaviour in all the different composites, which indicates that the resin type also influences the impact resistance.

The measuring of shock properties indicates that higher consolidation pressures lead to higher shock velocities, mainly below impact velocities of 1100 m/s. The underlying effect is probably reduced porosity around the fibres. The increased shock impedance of the composite leads to higher contact pressures, more core deformation and stronger mushrooming, causing the substantially increased ballistic resistance of the resulting UHMWPE targets.

A very important finding of statistical analyses is the fact that experimental V_{50}'s can be very well predicted from depth-of-penetration measurements carried out at a single projectile velocity, even much below the V_{50}. In all different analysis types, scatter decreases and quality of fits improve with increasing consolidation pressures.

References

[1] van der Werff H., Heisserer U., High-performance ballistic fibres: ultra-high molecular weight polyethylene (UHMWPE), in : Chen X. (Ed), Advanced Fibrous Composite Materials for Ballistic Protection (Woodhead Publishing, 2016), pp. 71-107.
[2] Zheng J.Q., Walsh S.M., Lightweight Ballistic Composites (Elsevier, 2016), pp. 393-437.
[3] NATO/PfP, AEP-55, Volume 1 (Edition 1), Procedures For Evaluating the Protection Level of Logistic and Light Armoured Vehicles (February 2005), Annex D.
[4] O'Masta M.R., Deshpande V.S., Wadley H.N.G., Defect controlled transverse compressive strength of polyethylene fibre laminates, Int. J. of Solid and Structures, 52 (2015), 130-149.
[5] Bolz K., Hensellek S., Acher V., Veehmayer M., V_{50} Study of Light-Weight Body Armour Inserts under Angle Shot, PASS 2023: Proceedings, pp. 11-18.
[6] Singletary J. Carbajal L., Boogh L., Fragment Simulating Projectile V_{50} Scaling rules, PASS 2008: Proceedings, pp. 287-296.
[7] Laessig T.R., May M., Heisserer U., Riedel W., Bagusat F., van der Werff H, Hiermaier S.J., Effect of consolidation pressure on the impact behaviour of UHMWPE composites, Composite Part B, 147 (2018), 47-55.
[8] Meyers M.A., Dynamic Behavior of Materials (John Wiley & Sons, New York, 1994), pp. 103-109.
[9] Riedel W., Wicklein M., Thoma K., Shock properties of conventional and high strength concrete: Experimental and mesomechanical analysis, Int. J. of Impact Eng., 35 (2008), pp 155-171.

DISCLAIMER

All information, data, recommendations, etc. relating APM Dyneema products (the Information) is supported by research. APM however assumes no liability arising from (i) the application, processing or use made of the information or products; (ii) infringement of the intellectual or industrial property rights of third parties by reason of the application, processing or use of the Information or products by the buyer. Buyer shall (i) assume such liability; and (ii) verify and/or test the Information and the products before use.

'Dyneema®' and 'Dyneema®, the world's strongest fibre™' are trademarks of APM.
Use of these trademarks is prohibited unless explicitly authorized.

https://doi.org/10.52202/081621-0003