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Estimation of the Propagation of the Impact Wave Phenomenon as a Result of a Bullet Impact in PACVD-Modified Textiles

DOI: 10.5604/01.3001.0012.9989

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Abstract

This complex study was performed using Plasma Assisted Chemical Vapour Deposition (PACVD) modification of ultrahigh molecular weight polyethylene (UHMWPE) fibrous composites and pararamid fabrics with deposition of a fluoro- or silane-like-polymer onto their surface. Research on the phenomenon of the propagation of the shockwave resulting from a bullet hit in an insert model system was performed on the basis of the PN-V-87000:2011 Standard, with the use of 7,62 x 25 TT 5,5 ± 0,1 g bullets. To assess the phenomenon of propagation of the shockwave resulting from a bullet hit in the insert model system, an ultrahigh-speed digital camera was used. The behaviour of the shockwave resulting from the hit of a bullet on the surface of the model insert systems studied depended greatly on the type of textiles introduced to the system. Modification with low-temperature plasma in the presence of vapours of low-molecular-weight fluorinated or silanogenic substrates positively affected the stability of ballistic properties during accelerated aging of woven fabrics and unwoven sheets.

Key words: PACVD-modified textiles, ballistic behaviour, ballistic compositions, accelerated ageing.

Introduction

The main critical parameter of ballistic protectors of the body is stability of the functionalities, including ballistic resistance during the sequencing of storing and long-term use. Several studies [1, 2] tried to modify ballistic textiles in the aspect of prolongation.

A complex study was performed using Plasma Assisted Chemical Vapour Deposition (PACVD) modification of soft UHMWPE fibrous composites and p-aramid fabrics with deposition of a fluoro- or silane-like-polymer onto their surface [3]. The mechanical and physical make-up of the PACVD-modified textiles was constructed with the selection of the most optimal materials for designing models of ballistic system. Moreover the effect of accelerated ageing using two types of aging factors: temperature and temperature and humidity on the main physico-mechanical structural properties was tested in [4, 5]. The process of the accelerated ageing of newly developed textiles showed the significant effect of the surface-deposited polymer on the main functionalities of the ballistic textile. Changes in the properties differed in relation to the type of accelerated ageing factor and deposited polymers and textile carrier used. The increase in the hydrophobicity of the PACVD-modified materials affected resistance against the negative effects of accelerated aging.

Additionally ballistic tests (bullet- and fragments-proofness) of the ballistic systems designed based on PACVD-modified textiles after accelerated aging were performed [6]. The systems of PACVD-modified textiles indicated significantly better resistance in the conditions tested.

The impact of the projectile causes the wave motion of particles placed in the same plane, which at the time of observation have the same phase value. In fact, we observed this in the form of propagation over the projections and valleys. The impact pulse spreads along the length and width of the layers of the protective material. The pulse propagation velocity is identical to the speeds of propagation of sound waves in the material [7]. Among the materials for ballistic shields against the highest speed of propagation of the sound wave, there are the fibres produced by Dyneema (above 10 km/s). Hence the goal is to obtain solutions which provide the maximum velocity of propagation of the shock wave. The energy of the projectile impact is more likely absorbed by a multilayered ballistic shield, reducing the possibility of local destruction and trauma [8]. Analysis of the profile of the elastic wave propagated is undertaken in resistance tests of a wide variety of materials, not only intended for use as ballistic shields [9-12].

The PACVD-modifications of the ballistic textiles significantly changed their

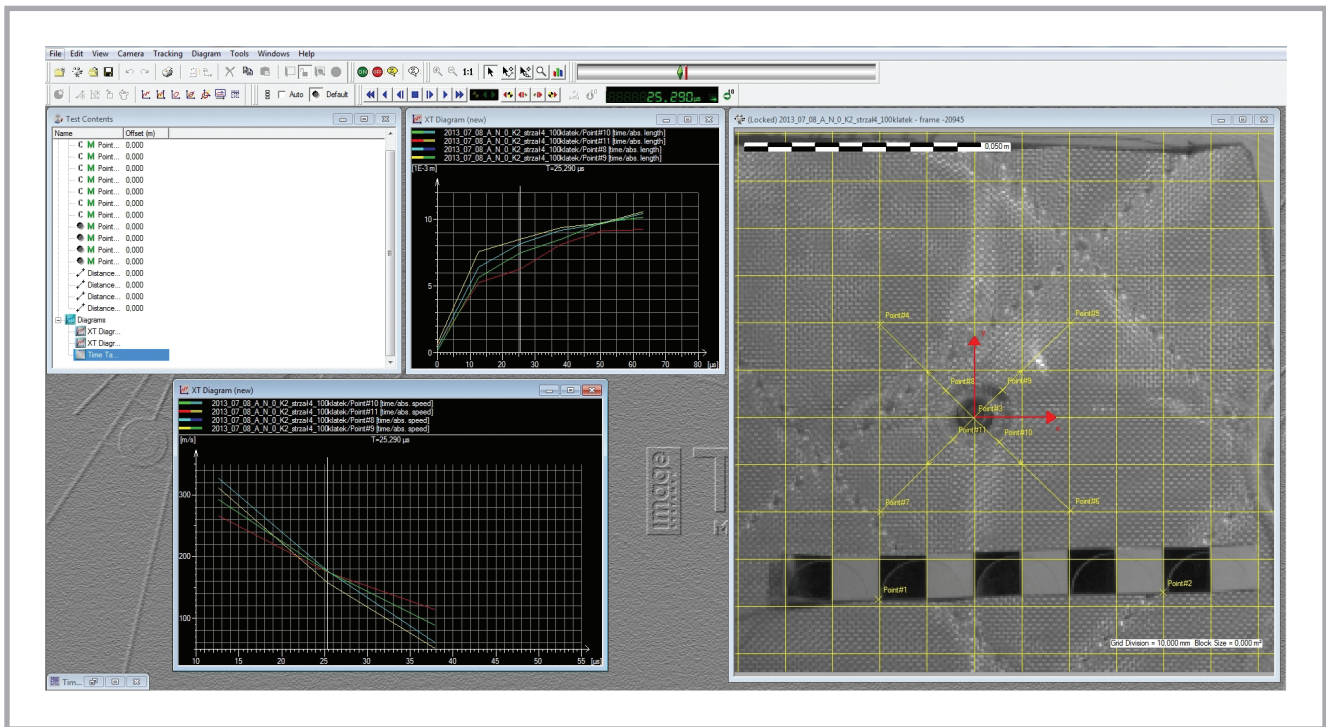


Figure 1. Example of the analysis of the shockwave propagation resulting from a bullet hit in the insert model system, with the use of TEMA MOTION – Image Systems v 3.7 software.

mechanical and physical properties. The alteration observed in the mechanical and physical performance of soft UHMWPE fibrous composites and p-aramid woven fabrics after the plasma-deposited polymer should change the ballistic effects. Thus the research aimed at the description of the phenomenon of ballistic wave propagation in relation to the following: 1) the type of textile carriers used for PACVD-modification, 2) the type of polymer deposited during PACVD deposition, and 3) the effect of accelerated aging.

Materials

Textile materials

Two types of ballistic textiles were used in the study:

- Style 363/120 woven fabric (SAATI S.P.A, Italy) made of p-aramid yarns;
- Dyneema® SB51 UHMWPE fibrous composite (DSM/The Netherlands) [13].

Substrates for PACVD (Plasma Assisted Chemical Vapour Deposition)

The Dyneema SB51 was PACVD-modified using heksametylodisiloksan ($C_6H_{18}OSi_2$; HMDSO) from Sigma Aldrich, whereas the p-aramid woven fabric was modified using tetrafluoroethane; $CF_3(CF_2)_4CF_3$; (TDFH), 99%, Tokyo Chemical Industry/Japan.

Methods

Surface modification of Dyneema® SB51 by PACVD

The modification of Dyneema® SB51 in glow discharges was performed in a commercial plasma reactor – CD 400PLC ROLL CASSETTE (EUROPLASMA/ Belgium) according to [14].

Accelerated ageing

In order to perform tests of ballistic properties and accelerated ageing during the optimisation research, ballistic insert model systems were designed that constituted ballistic packets according to [6].

The process of accelerated ageing of the ballistic insert model system (modified and unmodified variant) was carried out according to [14].

Impact study

Research on the phenomenon of propagation of the shockwave resulting from a bullet hit in the insert model system was performed on the basis of the PN-V-87000:2011 standard, with the use of 7,62 x 25 TT 5,5 ± 0,1g bullets with a lead core and bimetallic jacket at a velocity of 420 ± 15 m/s (class K2) according to [6].

To assess the phenomenon of propagation of the shockwave resulting from a bullet hit in the insert model

system, a ultrahigh-speed digital camera – PHANTOM v711 with a panoramic CMOS sensor of a resolution of 1280 x 800 pixels was used.

The phenomenon was recorded with PHANTOM – Vision research v1.33.697.0 software and analysed with other software: TEMA MOTION – Image Systems v 3.7, suitable for processing the dynamic phenomena (*Figure 1*).

Parameters of measurement with PHANTOM – Vision research v1.33.697.0 software:

- Resolution – 256 x 256 pixels;
- recording speed rate – 79069 frames/s;
- exposure time – 12,292 ms;
- calibration was done using the calibration array.

Results and discussion

Packet model systems made of unmodified or modified p-aramid woven fabrics

Figure 2 presents the dependence of the rate of speed decrease of the shock wave propagation on time on the surface of the packet model systems made of unmodified p-aramid woven fabric at t various stages of accelerated ageing where only the temperature was applied as the ageing factor.

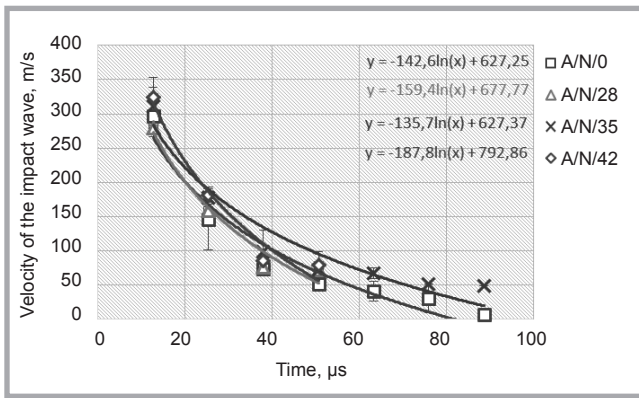


Figure 2. Dependence of the rate of speed decrease in the shock wave propagation on time in the surface of packet model systems made of unmodified p-aramid woven fabric at the various stages of accelerated ageing where only the temperature was applied as the ageing factor; A/N/x – system of the unmodified woven fabrics aged x days.

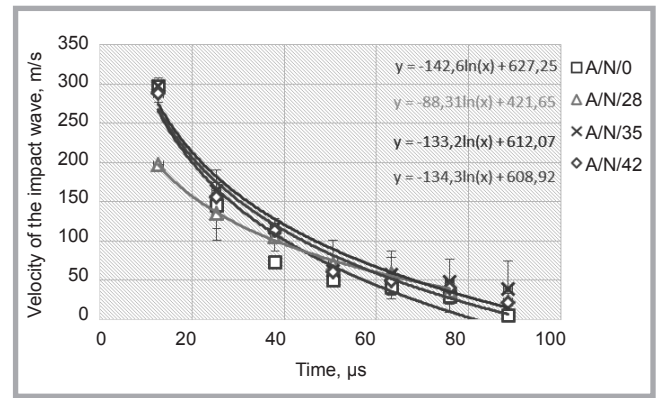


Figure 3. Dependence of the reduction in the shock wave speed of propagation on the surface of model packet systems made of unmodified p-aramid woven fabrics on time at various stages of accelerated ageing where the temperature together with humidity was applied as the ageing factor; A/N/x – a system of unmodified woven fabric aged x days.

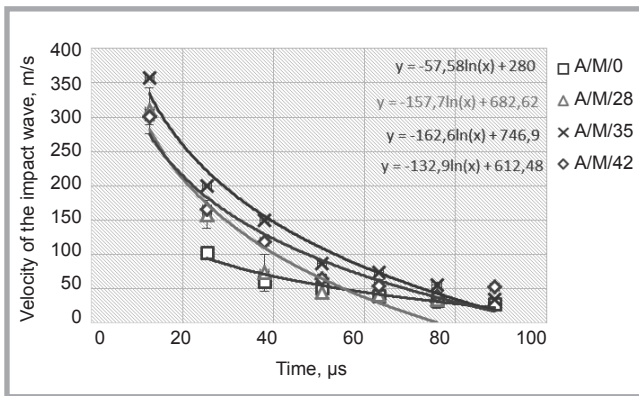


Figure 4. Dependence of the reduction in the shock wave speed of propagation on the surface of model packet systems made of modified p-aramid woven fabrics, at various stages of accelerated ageing, where the temperature alone was applied as the ageing factor; A/M/x – system of PACVD-modified fabrics aged x days.

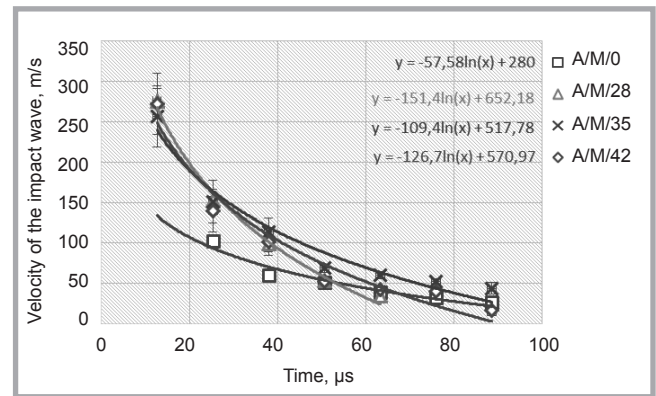


Figure 5. Dependence in the shock wave propagation speed decrease on the surface of model insert systems made of the modified p-aramid fabrics on time at the various stages of accelerated ageing where temperature together with humidity was the ageing factor; A/M/x – system of PACVD-modified fabrics aged x days.

In the process of accelerated ageing of packets made of the unmodified woven fabrics performed with the temperature factor, after the first stage of ageing, it resulted in faster absorption of the shock wave propagating on the surface of the model packet system being tested. At the next stage of accelerated ageing (35 days), a subsequent extension of the time to shock wave extinction was observed, to a value higher than that observed in the initial packets not exposed to the process of accelerated ageing. Further prolongation of the accelerated ageing process led again to an increase in the intensity of absorbing the shock wave on the surface of the samples tested.

Figure 3 presents the dependence of the rate of speed decrease of the shock wave propagation on time on the surface of packet model systems made of unmodified p-aramid woven fabric at the various

stages of accelerated ageing where temperature with humidity was applied as the ageing factor.

The process of accelerated ageing where temperature with humidity was applied as the ageing factors caused an extension of the time necessary to reduce the shock wave speed, especially at the first stage upon bullet impact observed on the surface of model packet systems made of unmodified p-aramid woven fabrics. After only 28 days of accelerated ageing, a change in the dynamics of shock wave propagation in the packet surface was observed. A similar trend continued after the next stages of accelerated ageing.

The dependence of the reduction in the shock wave speed of propagation on the surface of model packet systems made of the modified woven fabrics on time at various stages of accelerated ageing

where the ageing factor was only the temperature is presented in **Figure 4**.

The packet model system made of modified p-aramid woven fabrics was characterised by increased susceptibility to a decrease in the shock wave propagation speed, especially until ca. 40 μs upon impact of the bullet, compared to the effect observed in the packets made of unmodified woven fabrics. It may be linked to the greater tendency of the modified packets to local (punctual) absorption of the bullet's impact energy. Next in the packets of modified fabrics, the process of shock wave extinction lasted apparently longer than that observed in packets of the unmodified fabrics.

The process of accelerated ageing of the model insert systems made of modified p-aramid fabrics with temperature as the ageing factor caused an elongation of

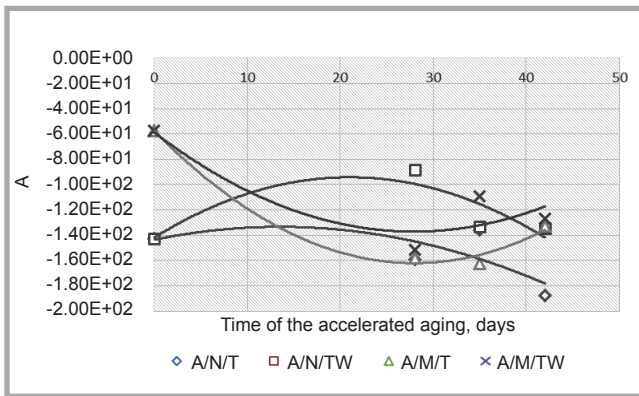


Figure 6. Dynamics of changes in the shock wave speed upon a bullet impact on the surface of model insert systems made of the fabric compositions on the time of accelerated ageing and kind of textile material applied; A/N/T – a system of unmodified fabrics aged with the use of temperature; A/N/TW – a system of unmodified fabrics aged with the use of temperature and humidity; A/M/T – a system of the modified fabrics aged with the use of temperature; A/M/TW – a system of the modified fabrics aged with the use of temperature and humidity.

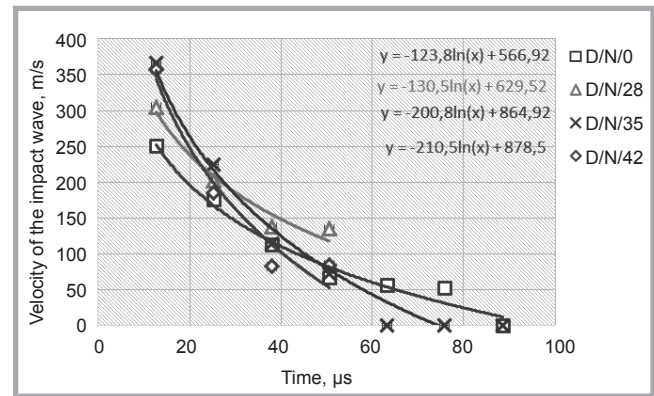


Figure 7. Dependence of the propagation speed of the shock wave on time on the surface of model insert systems made of unmodified unwoven sheets at various stages of accelerated ageing where temperature alone was applied as the ageing factor; D/N/x – x day aged packet.

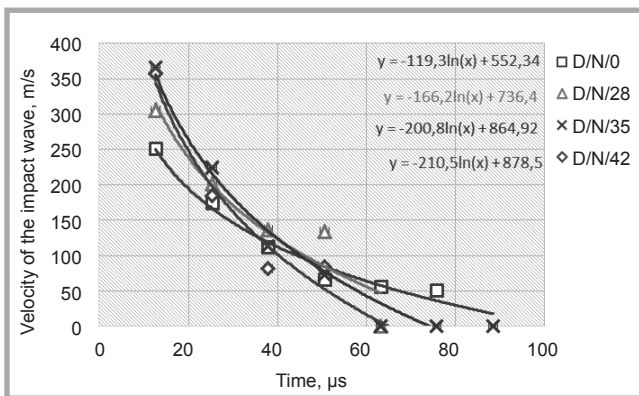


Figure 8. Dependence of the decrease in the shock wave propagation speed on time on the surface of model insert systems made of unmodified unwoven sheets at various stages of accelerated ageing where the temperature together with humidity was applied as the ageing factor; D/N/x – x day aged packet.

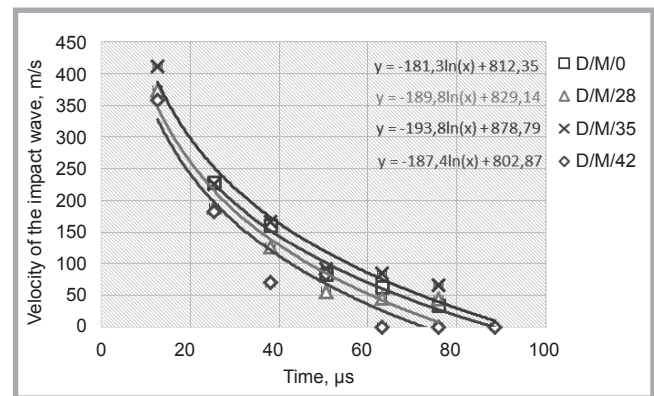


Figure 9. Dependence of the decrease in shock wave propagation on time on the surface of the model insert systems made of modified unwoven sheets, at the various stages of accelerated ageing, where the temperature alone was applied as the ageing factor; D/M/x – x day aged packet.

the time necessary to reduce the shock wave propagation speed in the first 60 ms upon impact of the bullet on the packet tested. A tendency towards a significant reduction in the shock wave speed within 60 ms upon impact of the bullet was observed in the packets aged 28 days, while those aged 35 and 42 days showed a lower dynamic of shock wave speed reduction within 20 ms upon impact of the bullet (35 days of accelerated ageing) or within the entire course of the shock wave (42 days of accelerated ageing). This phenomenon may enlarge the packet surface involved in the absorption of the bullet's impact energy.

The dependence of the shock wave propagation speed decrease on the surface of model insert systems made of the modified p-aramid fabrics on time at the various stages of accelerated ageing where

temperature together with humidity was the ageing factor is presented in **Figure 5**.

Phenomena similar to those previously described were observed in model insert systems made of the modified fabrics subjected to the accelerated aging process involving temperature together with humidity. Based on an analysis of the research, we can conclude that in the process of ageing the modified fabrics, the key ageing factor that affects the behaviour of the material in the process of absorbing the bullet's impact energy is the temperature. Furthermore various dynamics of changes in the shock wave speed were observed in dependence on the type of system: comprising fabrics modified or not.

To visualise the trends (also with regard to two different aging factors) that oc-

cur in the process of accelerated ageing of model insert systems that comprise the modified or unmodified fabrics (the initial material), the dependence of the "A" coefficient on the time of accelerated ageing was plotted (from the function $F(x) = A \ln(x) + B$) (**Figure 6**).

The behaviour of the shock wave on the surface of the model insert systems tested depended significantly on the modification of p-aramid fabrics or the lack of it. Moreover a different dynamic of propagation of the shock wave was observed in the packets designed with unmodified fabrics in dependence on the ageing factors applied, while maintaining a similar trend of changes. In the packets of modified fabrics, a similar trend was observed (opposite to that of the packets of unmodified fabrics), but with less difference in dynamics due to the conditions (ageing

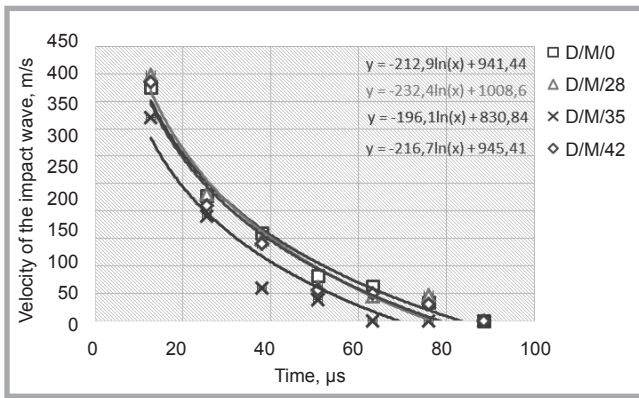


Figure 10. Dependence of the deceleration on time of the shock wave propagation on the surface of the model insert systems made of modified unwoven sheets at different stages of accelerated aging, where the temperature and humidity were used as the aging factors; D/M/x – a system aged x days.

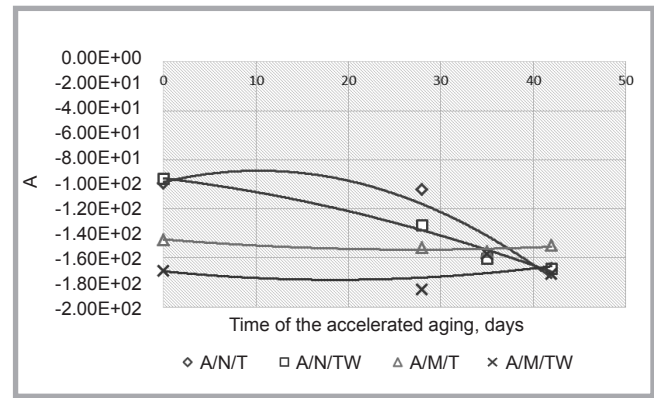


Figure 11. Dynamics of changes in the shockwave speed upon the impact of a bullet on the surface of model insert systems made of unwoven sheets over the time of accelerated ageing and textile material applied; D/N/T – system of unmodified sheets aged with temperature alone; D/N/TW – system of unmodified sheets aged with temperature and humidity; D/M/T – system of modified sheets aged with temperature alone; D/M/TW – system of modified sheets aged with temperature with humidity.

factors) of the process of accelerated ageing applied.

Model insert systems of unmodified or modified unwoven sheets of UHMWPE fibres

In the case of model insert systems based on modified or unmodified unwoven sheets made of UHMWPE fibres, research on the propagation of the shock wave was significantly hampered by the relatively high rigidity of the material. This enabled to analyse single shots and or the shock wave speed to a limited degree.

Figure 7 presents the dependence of the decrease in shock wave propagation on time on the surface of the model insert systems made of unmodified unwoven sheets at various stages of accelerated ageing where temperature alone was applied as the ageing factor.

The process of the accelerated ageing of packets of unmodified unwoven sheets performed with the temperature agent at various stages of accelerated ageing caused a reduction in the dynamics of shockwave propagation in the period of 25–30 μs upon impact of the bullet on the packet tested. Moreover an increase was observed in the dynamics of speed reduction of the shock wave after 40–45 μs upon impact of the bullet on the packet samples after 35 days of the accelerated ageing process.

The dependence of the decrease in the shock wave propagation speed on time on the surface of model insert systems

made of unmodified unwoven sheets at various stages of accelerated ageing where temperature together with humidity was applied as the ageing factor is presented on **Figure 8**.

Similar phenomena were observed when accelerated aging was performed using temperature together with humidity. Elongation of the process of accelerated ageing caused:

- a reduction in the dynamics of the shock wave speed decrease within the time scope of 35 μs upon impact of the bullet on the packet made of unmodified unwoven sheets tested, and
- a reduction in the dynamics of speed decrease after 40 μs upon impact of the bullet.

This was particularly clear in the packages subjected to an accelerated aging period longer than 35 days.

The dependence of the decrease in shock wave propagation on time on the surface of the model insert systems made of modified unwoven sheets, at the various stages of accelerated ageing, where the temperature alone was applied as the ageing factor, is presented on **Figure 9**.

The model insert system made of the modified unwoven sheets exhibited a tendency towards a reduction in the shock wave propagation speed, similar to the packets of unmodified sheets.

The process of accelerated ageing with the use of temperature as the ageing factor performed on the model insert sys-

tems of modified unwoven sheets did not remarkably alter the tendency of the shockwave speed changing over time.

After 42 days of accelerated ageing, an increase in the dynamics of shockwave speed reduction was observed, as compared to the packet not exposed to the process of accelerated ageing.

Figure 10 shows the dependence of the deceleration on time of the shock wave propagation on the surface of the model insert systems made of modified unwoven sheets at different stages of accelerated aging, where the temperature and humidity were used as the aging factors.

In the case of model insert systems of modified unwoven sheets exposed to the process of accelerated ageing with temperature together with humidity, the dynamics of shock wave deceleration were slightly greater than those observed when the ageing factor was temperature alone. In summary, as in the case of the model insert systems comprising the modified or unmodified p-aramid fabrics, the packets of unwoven sheets showed various dynamics of changes in the speed of shock wave propagation depending on the type of system: comprising unwoven sheets that were modified or not.

As for the fabric packages, in order to visualise the trends of changes in the accelerated aging (also with respect to two different ageing factors) of the model insert systems comprising the unwoven sheets, modified or not (the initial material), the dependence of coefficient A on

the time of accelerated aging was established (*Figure 11*).

The behaviour of the shock wave on the surface of the model insert systems studied depended remarkably on the presence of the modified unwoven sheets in the insert tested.

In the inserts produced with unmodified unwoven sheets, various dynamics of shock wave propagation were observed, while the tendency of changes resulting from the accelerated aging process was similar. In the inserts made of modified unwoven sheets, this tendency was observed, irrespective of the ageing factors, and the dynamics were different from those observed in the packets comprising unmodified sheets.

■ Conclusions

The behaviour of a shockwave resulting from the impact of a bullet on the surface of the model insert systems studied depended greatly on the type of p-aramid textiles introduced into the system. The inserts of unmodified textiles showed various dynamics of shock wave propagation depending on the ageing factors applied (temperature or temperature and humidity), while they maintained a similar tendency of changes. After the first stage of the ageing process, there was faster absorption of the shock wave propagating on the surface of model packet system being tested. At the next stage of accelerated ageing (35 days), a subsequent extension of the time to shock wave extinction was observed, to a value higher than that observed in the initial packets not exposed to the process of accelerated ageing. Further prolongation of the accelerated ageing process led again to an increase in the intensity of absorbing the shock wave on the surface of the samples tested.

The inserts of the modified material showed a similar tendency to that when applying various ageing factors (yet opposite to that in the inserts of unmodified fabrics), with a smaller dynamics range in relation to the conditions (ageing factors) of the accelerated ageing process applied.

The research on the propagation of the shock wave in the modified or unmodified unwoven sheets made of UHMWPE fibres was significantly hampered by the relatively high rigidity of material, ena-

bling to analyse single shots and or the shock wave speed to a limited scope.

In the inserts of unmodified nonwoven sheets produced, various dynamics of shockwave propagation were observed, with a similar trend of changes resulting from the accelerated ageing process. In the inserts of the modified unwoven sheets, the tendency of changes and their dynamics were independent of the ageing factors, but different than those observed in the inserts comprising the unmodified ones first increases and then decreases, while for the modified ones the situation is reversed.

It should be emphasised in the conclusion that modification with low-temperature plasma in the presence of vapours of low-molecular-weight fluorinated or silanegenic substrates alters the properties of woven fabrics and unwoven sheets. No case of full piercing occurred in the model insert systems made of textile materials subjected to modification with PACVD). It affected the stability of ballistic properties positively during accelerated aging, as well as altering the effect of the generation and propagation of the shock wave from a bullet impact both in the initial materials and those exposed to the accelerated aging process. PACVD modification allows to prevent the destructive influence of humidity during the aging process.

Acknowledgements

The research was supported by the National Science Centre under research project No N N508 629940. The studies on the functionalisation of ballistic materials.

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□ Received 14.09.2017 Reviewed 17.01.2018