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TEXTILE BALLISTIC SHIELDS WITH EMBROIDERED STRUCTURE

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ABSTRACT

Textile ballistic shields are the basis of protection against bullets and fragments with low kinetic energy. They are usually made of para-aramid fabrics or UD sheets of HPPE. The aim of the research presented in this article was to obtain ballistic packages made of embroidered structures and to compare their ballistic properties with those of woven structures, in terms of deformation of the standardised ballistic substrate after impact with a 9 mm bullet at a velocity of 380±3 m/s. The embroidered structures were made by embroidering two sets of para-aramid threads at an angle of 90°. As with the woven structures, the use of para-aramid fabric made of the same yarn and with a surface weight comparable to that of an embroidered structure, was adopted. The ballistic packages consisted of 26 layers in five variants, taking into account the hybrid arrangement of woven and embroidered layers. Ballistic tests have shown that the best ballistic properties have hybrid packages made by folding 13 woven and then 13 embroidered layers, where the maximum deformation of the plasticine substrate was below 23 mm. The conducted research confirmed that embroidered structures can significantly improve the ballistic properties of textile packages when appropriately combined with woven structures.

KEYWORDS

Ballistic packet, para-aramid embroidered fabric, para-aramid woven fabric, ballistic performance.

INTRODUCTION

Embroidery is traditionally known as a conventional technique of decorative textile processing that is found in almost every world culture and dates back to ancient civilizations. As part of the industrial revolution, embroidery entered mass production and its technical scope has significantly expanded with technological progress [1]. Embroidery techniques are often used in intelligent textiles, allowing uses such as: the deposition of LEDs on textile substrates [2], electrically conductive yarns (producing electrically conductive lines) [3], biomedical textile sensors (used in cardiological diagnostics), activity and pressure measurements, textile antennas and magnetic coils [4–6], as well as specialised yarns to produce composites with programmable strength properties [7].

Textile ballistic shields are the basis of human protection against bullets fired from handguns. Their effectiveness is related to preventing overshoot of the ballistic packet and limiting the ballistic trauma resulting from the quickly changing deformation of the packet in the area of the bullet impact. They are mainly made of para-aramid and ultra-high molecular weight polyethylene (UHMWPE) fibres, however, in addition to the unique properties of this material, there are also various mechanisms that must be considered, in order to increase the ballistic performance of the final ballistic package. A simple method to improve ballistic protection against ballistic impact is to add more layers in different settings during ballistic panel fabrication [8–9]. Although increasing the number of layers of a ballistic target improves its ballistic performance, it also affects the overall weight and flexibility of the target shield

[9]. At present, aramid fabrics with a plain weave or non-woven structures, based on polyethylene fibres, are used as the layers of ballistic packages. There are also high hopes for the development of multi-axis fabrics, however, the technology for producing such fabric has yet to be developed [10]. Another area of development for the flat materials used in ballistic shields is structures laid with straightened threads. Such attempts were carried out by gluing strands of threads together [11]. Research has shown that such structures are characterised by lower transverse deformation during bullet impact, compared to conventional fabrics. Problems associated with these structures relate to thread spreading at the point of impact of the bullet. Due to the dynamic development of embroidery machines, it seems that such structures can also be formed by the embroidery method. The specificity of this method should give a wide range of possibilities for the methods of thread laying, thus influencing the ballistic properties of the covers. This article presents research into obtaining ballistic packages made of embroidered structures and comparing their ballistic properties with woven structures, in terms of the deformation of the standardised ballistic substrate after being hit by a 9 mm Parabellum bullet at a speed of 380±3 m/s.

MATERIALS AND METHODS

The commercially available Twaron CT709 Microfilament 930 tex f1000 fabric (Teijin Aramid, Netherlands), characterised by the number of threads in both systems (105 threads/dm) and surface weight of 200 g/m^2, was used for the tests (Fig. 1b). The embroidered structure was made of the same yarn as the fabric, which was fastened to the main thread to the PP spun-bonded nonwoven substrate in a zigzag pattern, with an area weight of 80 g/m^2 (TEXFIL, Poland) using a thread TYTAN 360 (Ariadna, Poland) with an average linear weight of 85 dtex. The embroidered structures were made with a JCZA 0109-550 embroidery machine (ZSK Stickmaschinen, Germany), where two sets of para-aramid yarns were arranged at an angle of 90°. The first thread system was cross-embroidered to the non-woven backing. In turn, the second thread system was attached to the first thread system in a similar manner and at an angle of 90° (Fig. 1a). The woven and embroidered structures were used to make five variants of ballistic packages consisting of 26 layers with dimensions of 20 cm × 20 cm. The different variants were arranged as follows: Variant I - 26 embroidered layers, Variant II - 13 embroidered and 13 alternating woven layers, Variant III - 13 embroidered layers on the front and 13 woven layers on the back, Variant IV - 13 woven layers on the front and 13 layers embroidered on the back, and Variant V - 26 woven layers (Fig. 1c), to compare the ballistic performance of woven, embroidered and hybrid packages. The number of layers of the packages was selected based on literature reports which show that the package made of 24 layers of Twaron CT709 fabrics, fired with a 9 ×19 mm Parabellum bullet at a speed of 364.85 m/s, exhibited a maximum deformation of the normalized plasticine substrate at the level of 30.5 mm [12]. Due to the higher velocity of the projectile used in the tests, the number of layers was increased to 26 so as to keep the deformation of the plasticine substrate at a similar level.

Figure 1. The method of making ballistic packages: a) embroidered structure, b) Twaron CT 709 fabric, c) variants of ballistic packages.

Three packages of each variant were prepared for firing at the Ballistic Research Laboratory. At a zero impact angle, one shot was fired using a 9 ×19 mm Parabellum FMJ bullet at the centre of each package placed on a standardised Roma No 1 plasticine substrate. During the firing, the impact of the bullet was recorded through a set of gates, to measure the velocity of the bullet. After the firing, the ballistic substrate was scanned with a laser distance sensor, the position of which was controlled by stepper motors. Each time an area measuring 18 cm × 18 cm was scanned, the centre point was always positioned at the largest depression of the plasticine substrate. After firing, the ballistic packages were also analysed for the number of overshoot layers. On this basis, the perforation coefficient was calculated as the ratio of the number of fully penetrated layers to the number of all layers in the ballistic packet.

RESULTS AND DISCUSSION

First, the maximum value of the deformation of the plasticine substrate was analysed for the five variants of ballistic package. Fig. 2 shows 3D plots of the plasticine substrate deformation for variants IV and III, which caused the lowest and the highest deformation, respectively.

a) b)

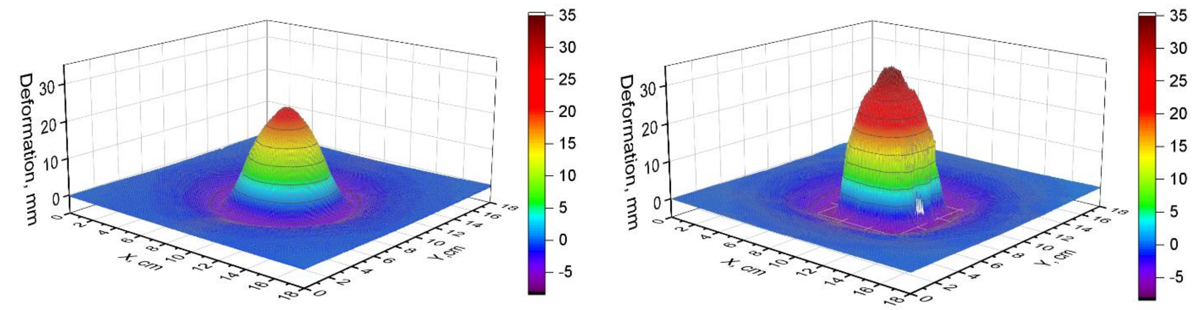

Figure 2. Plasticine substrate deformation after shooting packages: a) Variant IV, b) Variant III.

After firing the package in Variant III, the deformation of the plasticine substrate superimposed a pyramid and sphere shape which, in effect, gives the shape of a prism. This is the effect of the layer configuration used in this variant: the first layers were embroidered structures and the next were biaxial fabrics. The nature of the ballistic base deformation for Variant III is the result of relatively easy penetration of the embroidered structures by the bullet, due to the tendency to spread the threads around the point of impact. After piercing the layers with the embroidered structure, the bullet hits the biaxial fabric, which is characterised by thread entrainment and a lower speed of stress wave propagation, in relation to the straightened threads. This results in easy transverse deformation of the packet until the threads in the fabric stretch and the impact energy is concentrated on a small area around the point of impact of the bullet. The perforation factor for this type of packet equal to 0.52 was very unfavourable. It is assumed, that in packets used in commercial vests the perforation factor should be below 0.2-0.25.

In the event of a bullet hitting a package made using Variant IV, the bullet first penetrates the woven layers. Due to the interweaving threads of weft and warp, they are firmly jammed and do not have a tendency to slide apart. The deformation cone formed in the last woven layer affects the embroidered structures. However, it is much larger and no longer causes the threads to spread in the embroidered layers, in which, due to the stretched threads, the propagation of the stress wave is higher than in the fabric and the area covered by the impact energy is larger. This results in faster stopping of the bullet and significantly less deformation of the plasticine substrate. The perforation ratio for these packets was very favourable: 0.15. In order to compare the maximum values of deformation, cross-sections were made in the X, Y and XY planes (Fig. 3a). As can be seen from Fig. 3b-d, the lowest value of the maximum deformation of the plasticine substrate, amounting to 23 mm, was obtained when firing the package in Variant IV. After over shooting the remaining packages, the maximum deformation was higher and amounted to 24, 25, 30 and 35 mm for packages made in Variants II, I, V and III, respectively. Packets made of fabric only (Variant V), commonly used in practice, show significantly worse properties than the hybrid packets made in Variant IV. The maximum deformation of the substrate was higher by 6 mm, which should be considered a significant value due to the behind armour blunt trauma (BABT). Also, the perforation coefficient was higher and amounted to 0.2.

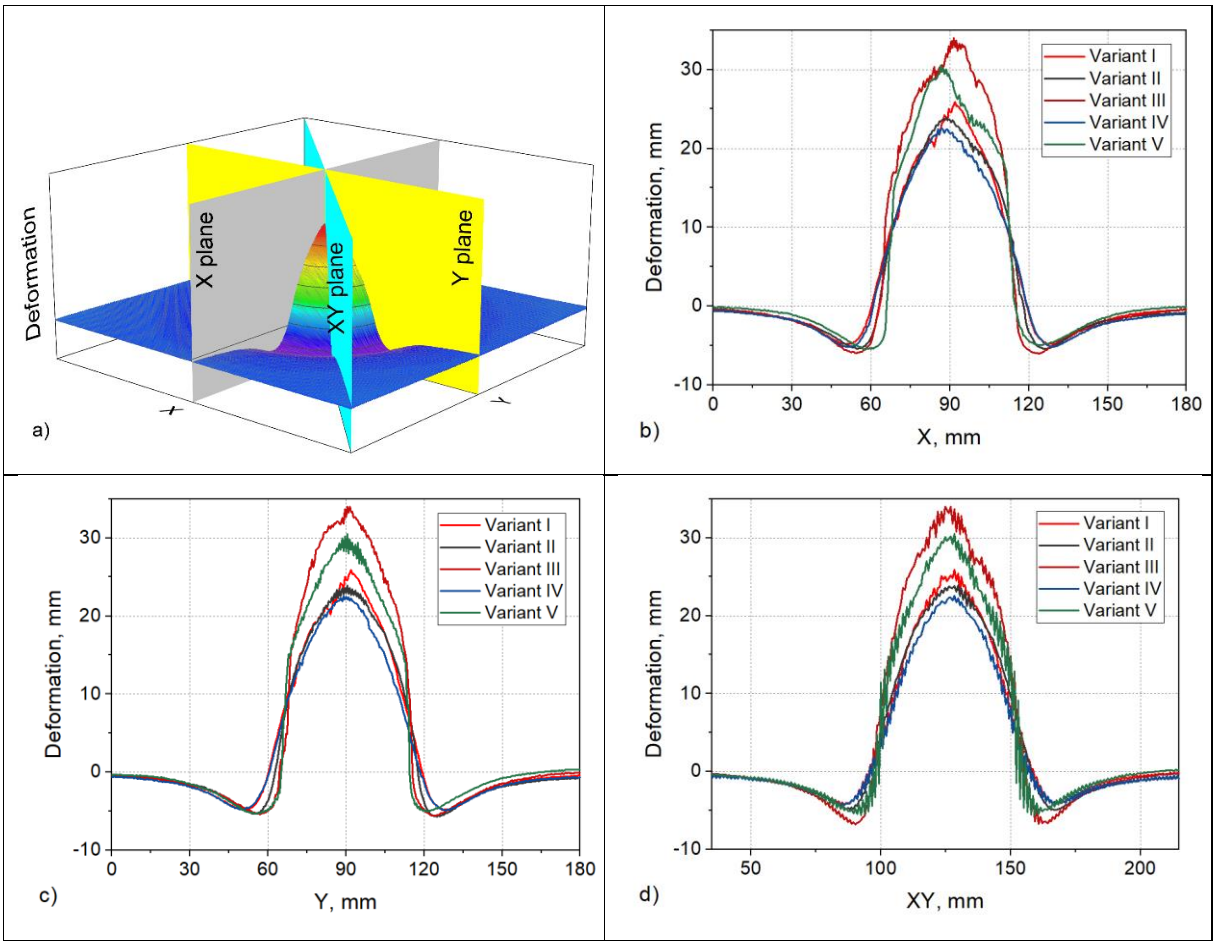

Figure 3. Plasticine substrate deformation: a) plane selection, b) in the X plane, c) in the Y plane, d) in the XY plane.

CONCLUSION

The article presents ballistic studies of para-aramid woven and embroidered structures, which, to date, have not been considered as layers of textile ballistic packages. The best ballistic properties are demonstrated by hybrid packages in which woven and embroidered layers are combined. On the one hand, the advantages of these structures in absorbing the projectile impact energy but, on the other hand, they limit the disadvantages of these structures, such as thread spreading in embroidered structures, warp and weft threads crimping, and low stress propagation speeds in woven structures. Skilful use of the positive features of woven and embroidered structures in contact with the bullet, allows for a ballistic package with excellent ballistic performance.

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