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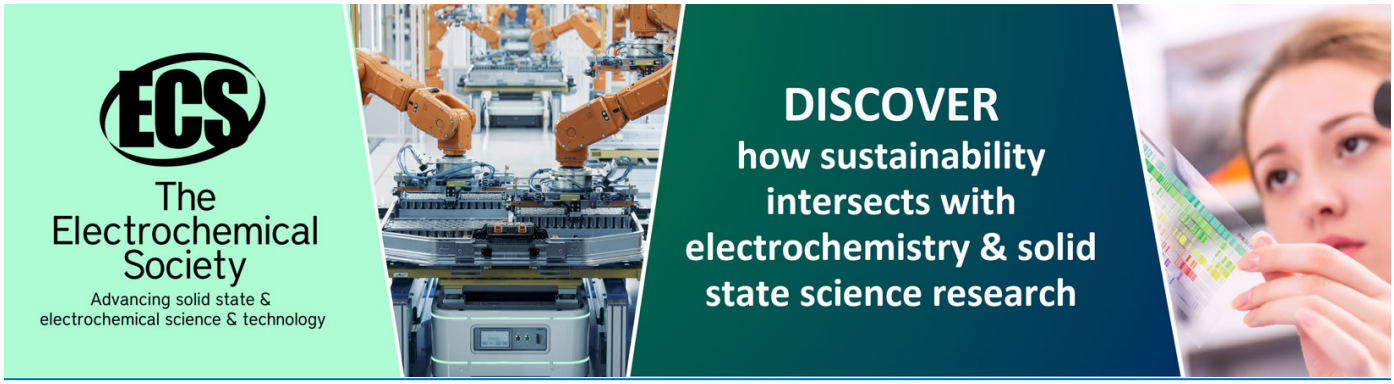

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The application of PA/CF in stab resistance body armor

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Abstract. Stab resistance body armor (SRBA) is an essential defensive equipment to protect human body against injuries from stabbing. The conventional SRBAs shared low wearing frequency since they are heavy and poor in flexibility. This paper designed a structured stab-resistance plate using the model of crocodile armor and manufactured using 3D printing technology-laser sintering (LS). CF(Carbon fiber) was applied to enhance the stab resistance properties of SRBA. The effects of the material and structure were analysed through the stab resistance property tests based on the national standard GA68-2008. It is found that the stab resistance property of flat plates sintered by PA powder and PA/CF are both weaker than that of the structured plate. The penetrating depth of PA/CF structured plate is significantly 2-mm-less than the pure PA structured plate. The SEM observations confirmed the conclusion that addition of the CF largely improved the plate stab resistance property. Moreover, using PA/CF structured plate to produce the stab resistance body armor would result in a weight reduction by about 30-40% as compared to the existing SRBA that was made up of metal plates, which could largely reduce the wearer physical burden and improve the wearing frequency.

Keywords: Laser sintering, Stab resistance body armor, Polyamide, carbon fiber, Bionic structure

1. Introduction

The number of terrorist attacks has increased rapidly in these years. In China, the use of gun is strictly restrained, thus the threat mainly comes from knives. According to a survey, 6,000 people were killed during the period 2011-2015 due to knife injuries. There were 500,000 cases reported, during 2009 to 2015, against illegal carriage of the restrained knives. Stab resistance body armor is essential equipment in protecting humans from knife injuries [1]. However the low wearbility results in low protection effect, which is mainly due to three reasons: firstly the conventional SRBA which used alloy materials is very heavy, of which the weight could reach 3.5-4.0 kg [2], causing heavy burden to the human body; secondly the SRBA shows low flexibility due to the integral plate design; thirdly the SRBA exhibits the low thermo-physical properties, of which the thermal insulation and vapour resistance are two times larger than that of a winter jacket [3]. The limited development of SRBA is mainly due to the limitation on material selection, structure design, and manufacturing methods: the conventional used materials include rigid panels (i.e. alumina, ceramic, etc.) or flexible panels (i.e. Kevlar fabric [2], UHMWPE fabric [3], etc.), which is either too hard or multi-layered due to the limitation on mechanical properties of the fabric. Therefore, an advanced type of SRBA is desired which would exhibit excellent stab resistance property while being light weight and more flexible.

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The stab resistance property is achieved as a collaboration of the material mechanical property and the designed energy dissipation structure. For centuries, scientists and designers have studied natural bio-protection layers in animals trying to find inspirations to develop innovative body armors. The first biological armor system could be traced back to 540 million years ago to the Paleozoic era where such evolved to provide protections against penetrating predatory attacks [4]. Many modern-day animals also possess armors, including mammals (e.g., armadillos and pangolin), reptiles (e.g. alligators, crocodiles, lizards) and numerous fish [5], which provide new solution for SRBA design. Yang et al [4] examined scales from several fish and mammals and concluded that the flexibility has been increased without significantly sacrificing strength by owning a hierarchical structure with collagen fibers joining more rigid units. It is pointed out the understanding of such flexible dermal armors is essential in that it may provide a basis for new synthetic armor materials. John [6] studied five classifications of scales containing placoid, ganoid, osteoderms, elasmoid and the pangolin. The scale size was calculated and it is stated when arranging the individual scale elements in an imbricated assembly way, it is possible to create a hierarchical structure capable of providing effective and flexible levels of protection against localized threat while minimizing back face deformation.

However, the fact that the animal armor could provide excellent inspiration for the SRBA structure design, the complex structure is difficult to realize in conventional manufacturing methods. Therefore, one solution to be explored, in an attempt to address these issues of developing naturally inspired body armor featuring complicated interlinked assemblies, is that of additive manufacturing (AM) [7]. Laser sintering (LS) is an additive manufacturing technology that employs a laser to fuse polymer powder into a mass that has the desired three-dimensional shape [8]. In this process, laser scanning of one surface layer is followed by addition of a new layer of fresh powder to the material surface which is then laser scanned to provide a new layer. The process is repeated until the desired part is fabricated. Laser Sintering is a typical AM method, which enables the designers to freely fabricate a part without the restrictions imposed by conventional design, manufacturing, and assembling methods [9].

Additive manufactured stab resistant body armor has been studied in recent years using LS technology. Johnson [10] first investigated the use of polyamide to fabricate LS planar materials. All of these products were found to meet to the Body Armor Standards for UK Police (2007) level one, able to resist impact energy of 24 Joules and a maximum permissible knife penetration of 7 mm [11]. It was found that the armors manufactured using a 50:50 mixture of virgin and recycled powder performed much better than those fabricated from virgin powder. The mechanical properties of the composites improved remarkably due to the addition of carbon fiber [12]. The standard demanded by Stab Resistant Body Armor National Standard published by the Ministry of Public Security of the People's Republic of China in 2008 (GA 68-2008)[13] requires that an acceptable personal body armor exhibit zero penetration when the stab impact energy is 24 J. More work such as using new materials to produce lighter SRBAs is needed in the development of body armor.

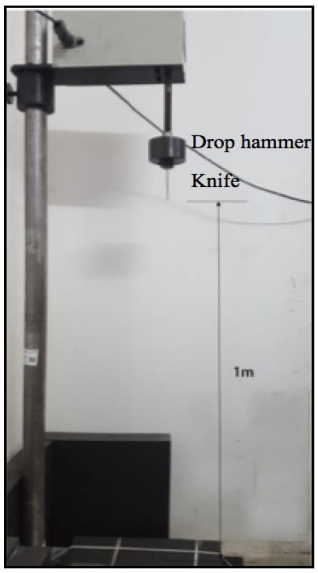
Therefore, in this study, research was conducted on four types of laser sintered materials to evaluate whether polyamide/carbon fiber (PA/CF) can be used as a material for making SRBAs to meet the requirements of the GA 68-2008 standard. Experiments were initially conducted on flat samples of various thicknesses to identify the optimum thickness. In further work a structured plate was designed and fabricated to improve the performance of the flat plates. The angle and thickness were analysed and discussed. The advantages of CF application was compared and investigated. This study established use of laser sintered polyamide for fabrication of stab proof personal body armor, which identifies a new approach for design, manufacturing and assembly of personal protective clothing design.

2. Methodology

2.1. Test standard

All stab resistance tests of the novel armor materials conformed to the GA 68-2008 National Standard [13]. The test platform comprised of a drop hammer, a knife, the test specimen and the backing

material (as shown in Figure 1). The total mass of the hammer and the knife was 2.4 kg, which was released vertically 1 m above the test material, in a free fall onto the test material which produced an impact energy of 24 J. The standard required that the body armor should resist any penetration from the test blade. The backing material was composed from top to the bottom of neoprene sponge, polyethylene plastic and natural rubber. All the tests were performed at ambient temperature of -20-55℃. The test apparatus used for the testing were purchased from Chengde Kecheng Testing Machine Co. LTD [14].



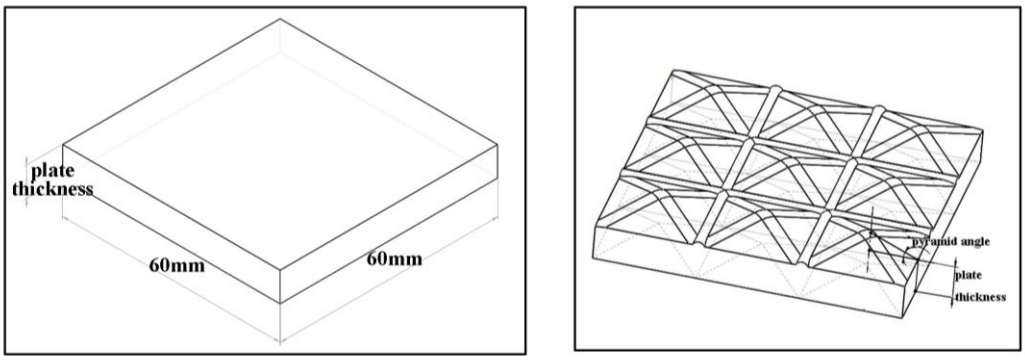
（a）

Figure 1. Stab resistance test platform.

2.2. Sample preparation

Four types of materials were employed for the LS fabrication: PA 3200, PA 4300, PA/GF and PA/CF. PA 3200 and PA 4300 were composed of polyamide 11 and 12 compositions. The PA/GF material was a composite comprising of 60.wt% polyamide and 40.wt% glass fiber. The PA/CF was a composite produced from70.wt% of polyamide and 30wt. % carbon fiber(CF). All the samples were fabricated using SolidWorks software. For each preparation, sample plates were fabricated with dimensions of 60×60 mm^2 as shown in Figure 2(a). For single layered specimens, the sample thicknesses were 9, 8, and 7 mm.

In order to test the excellent performance of PA/CF in different structures of the plates, the dimensions of the sample plates was set as 60×60 mm^2. In each direction (x and y), three pyramids were placed. The dimension of each pyramid was 20×20 mm^2, thus a total of 9 pyramids per test plate. As shown in Figure 2(b), the pyramid angle was measured from the back surface and the tilted pyramid ridge. The plate thickness was measured at the corner of the plate. The plate thickness was 6.5, 7, 7.5 mm separately, while the pyramid angle were 20, 25 and 30° which was accomplished via Solid works software.



(a) (b)

Figure 2. Overview of specimen structure (a) planar plate, (b) pyramid structured plate: a- pyramid angle, h-plate thickness, s-pyramid element length.

3. Results and discussion

3.1. Planar plates

Experiments were performed using the LS fabricated samples. Figure 3 shows an overview of the four types of specimens that were tested. The detailed experimental results are shown in Table 1. All the flat specimens failed in the experiment when the plate thickness is 7mm.

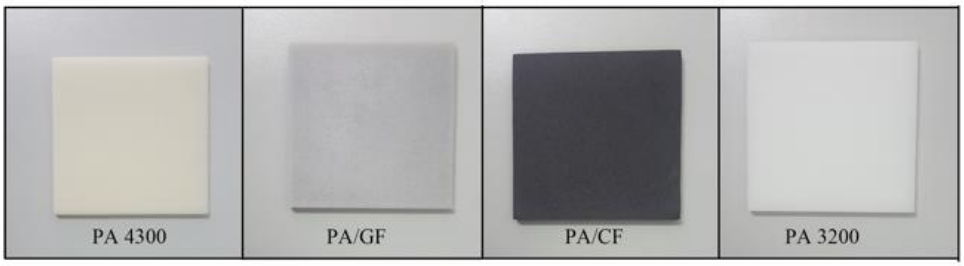
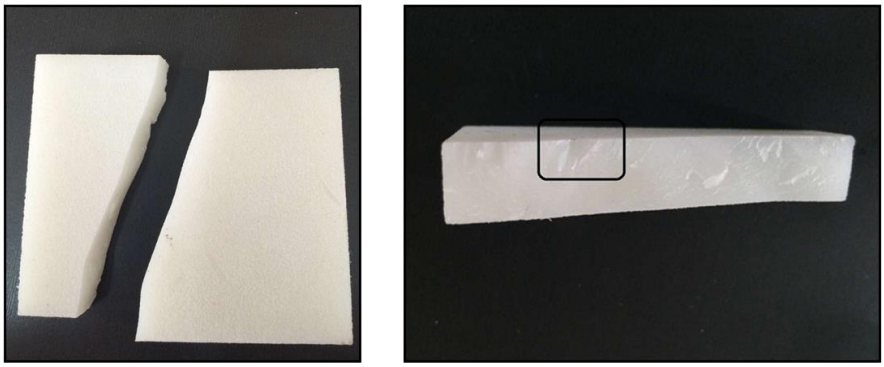


Figure 3. Overview of the four tested specimens before the stab resistance experiment, from left to right, laser sintered P4300, PA/GF, PA/CF, PA3200.

Table 1. Experimental results from the stab resistance experiments for four planar laser sintered materials.（√: success; ×: failure.）

Experiment arrangement		Material			
		PA 3200	PA4300	PA/GF	PA/CF
Plate thickness (mm)	Single layered	9(×)	9(×)	9(√)	9(√)
		8(×)	8(×)	8(√)	8(√)
		7(×)	7(×)	7(×)	7(×)

The specimens that passed the single layer experiment included the 8-mm-thick laser sintered PA/GF, 9-mm-thick laser sintered PA/GF, 8-mm-thick laser sintered PA/CF, and 9-mm-thick laser sintered PA/CF. Figure 4 shows a photo of the 9-mm-thick laser sintered PA 3200 specimen after the test, which was broken into two pieces. The highlighted black square shows the notch area where the blade entered. The 24 J-impact energy generated by the falling knife resulted in a brittle fracture in the specimen and the crack divided the specimen into 2 pieces. It was concluded that PA/CF had potential for penetration resistant applications.



(a) (b)

Figure 4. 8-mm-thick laser sintered PA 3200 after the stab resistance experiments (a) front view of the broken sample, (b) cross section view of the broken sample.

3.2. Structured plates

The structured plates were used to testify the stab resistant performance difference between PA 3200 and PA/CF. Experiments were performed with pyramid angles of 20°, 25°and 30°. The resulting plate thickness of the fabricated samples ranged between 6.5 to 7.5 mm. The detailed experimental results are shown in Table 2. As shown, the laser sintered PA 3200 exhibited a 50% rate of success in all the experiments, which included specimens that were 7-mm- thick with tilt angles of 25°and 30°and 7.5-mm-thick samples with tilt angles of 20°, 25°and 30°. The 6.5 mm thick samples failed in every test, because they were too thin. Test plates with thickness and greater tilt angles produced a higher possibility of success. For the laser sintered PA/CF composite, all the experiments were successful when the plate thickness ranged from 6.5 to 7.5 mm and the tilt angles ranged from 20° to 30°. The area densities of the laser sintered plates were measured before the tests, as shown in Table 2. The area densities were in the range of 7.27-8.14 kg/m^2, resulting in a total weight of 2.2-2.4 kg. This represented a 31- 37% less weight than the conventional SRBA.

The thickness of the structured plate played a fundamental role during the impact energy dissipation, longer sliding distance within the plate lead to less impact energy on the bottom of the plate. The pyramid angle helped to deflect the force of the knife tip; however, an acute angle produced a thinner pyramid and a shorter route to dissipate the kinetic, therefore the impact energy was sufficient to penetrate the plate. To achieve the optimal performance, there was a balance to be achieved between the plate thickness and pyramid angle: thicker plate leads to longer energy dissipation route as well as higher area density; larger pyramid angle leads to more improved energy dispersion efficiency as well as a week support from the bottom and shorter energy dissipation route.

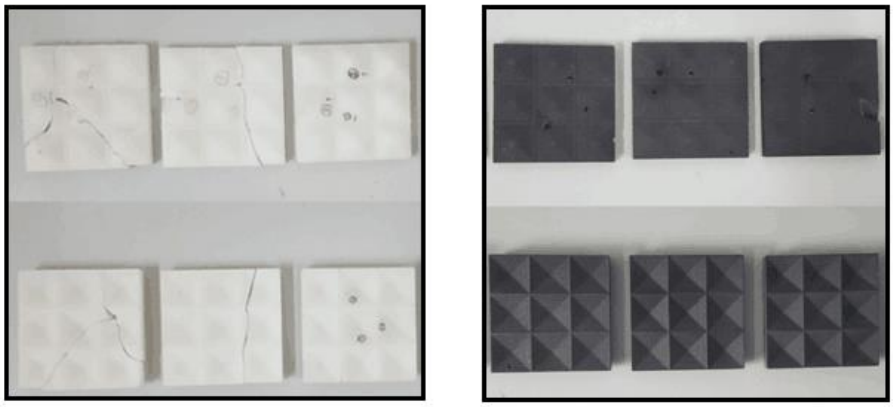
Table 2. Area density of the structured specimens (Note: ×: failure.)

Material	Thickness (mm)	Area density (kg/m^2) α=20°	α=25°	α=30°
PA 3200	6.5	6.53(×)	6.76(×)	6.88(×)
	7	7.51(×)	7.27(√)	7.56(√)
	7.5	7.90 (√)	7.68(√)	7.60(√)
PA/CF	6.5	7.41 (√)	7.04(√)	6.58(√)
	7	7.96 (√)	7.77(√)	7.29(√)
	7.5	8.14 (√)	8.02(√)	7.92(√)

Figure 5 shows the front and back views of the structure of the laser sintered PA 3200 and PA/CF following the penetration tests. Each specimen had a pyramid angle of 20° with plate thicknesses of

6.5, 7, and 7.5 mm from left to the right. It was found that the 6.5-mm-thick and 7-mm-thick laser sintered PA 3200 specimens were broken into pieces, while all of the laser sintered PA/CF remained intact with three small holes in each plate. No holes were observed at the back of the laser sintered PA/CF plates. The results indicated that the addition of the CF increased the penetration resistance of the sample.

Considering the experimental results and the total weight (area density), the optimum parameters needed to produce a successful stab resistant body armor fabricated using laser sintered PA/CF are: thickness of 6.5 mm with tilt angle of 30°. If the body armor was fabricated with 0.3 m^2 of protection, which is required by the GA 68 -2008 standard, the total weight would be 2.0 kg, which represent 57% of the weight of a conventional SRBA.



(a) (b)

Figure 5. Experimental test results from the structured laser sintered PA 3200 and PA/CF, with tilt angle of 20°, plate thicknesses of 6,5 7, 7.5 mm from left to the right, first row: front view, second row: back view, (a) laser sintered PA 3200, (b) laser sintered PA/CF.

The specimen structures were examined using scanning electron microscopy (SEM). Figure 6 shows the cross section of specimens that were laser sintered using PA 3200 and PA/CF. The plates were 7 mm thick with a pyramid angle of 20°. The laser sintered pure PA (top row) exhibited a smooth interface under 500×and 1000×magnification. The shear marks indicated the knife stabbing imprint and the track of the crack. The laser sintered PA/CF exhibited a very different interface. No agglomeration occurred and the carbon fiber were found to be homogeneously dispersed. The addition of the CF appeared to have prevented the knife from penetrating the bulk of the material by dissipating the impact energy. Thus the CFs appeared to contribute to the plate integrity based on the experimental results. In addition, it was demonstrated that the addition of CF increased sample's mechanical properties as a result of the high surface to volume ratio, and the high aspect ratio of the CFs [15].

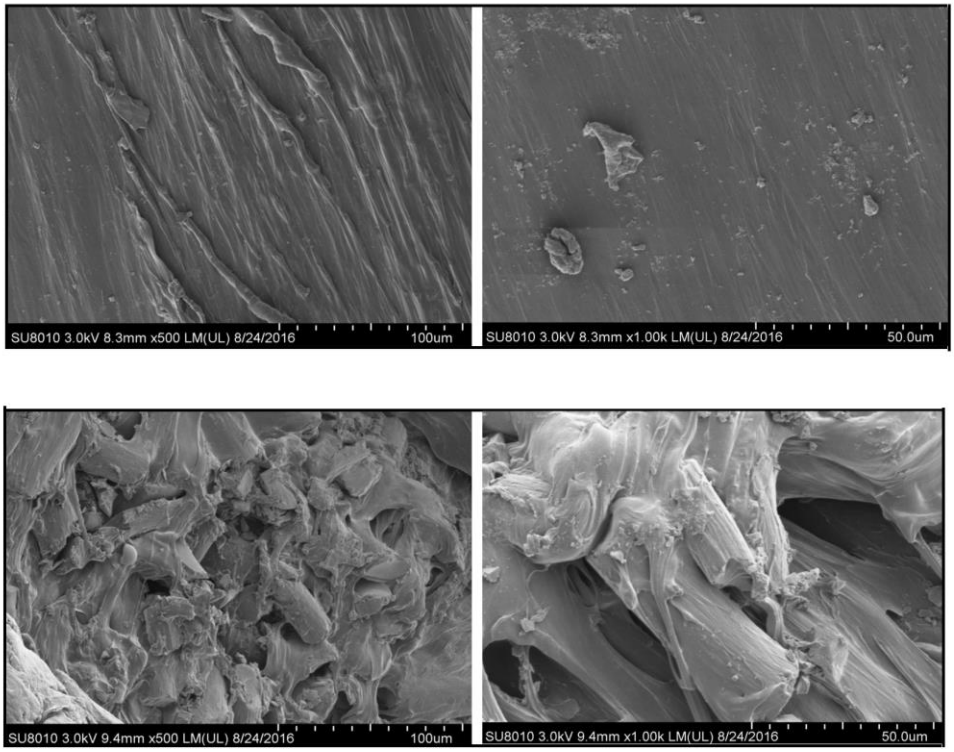


Figure 6. SEM images of the cross section of the structured specimen with a thickness of 7 mm and tilt angle of 20 °, laser sintered PA 3200 (top row), laser sintered PA/CF (bottom row).

4. Conclusion

In summary, natural animal armor inspired the structural design of stab resistance body armor (SRBA), and Laser Sintering (LS) technology was used to rapidly prototype the characteristics and the complexity of the desired structure. The pyramid structured plate was designed and optimum parameters were tested, discussed and achieved. The mechanism of the impact energy dissipation by the pyramidal structures of the novel SRBA was studied and it was found that this structure dispersed the deformation energy of the knife and minimized the damage to the plate. Four kinds of LS materials were prepared and tested based on the GA 68-2008 standard.

It was concluded that PA/CF was an optimum material for preparing a new armor for the desired stab resistant application. In the planar experiment, a minimum thickness of 8 mm of planar laser sintered PA/CF was required to achieve a suitable penetration resistance to an impact energy of 24 J based on the GA 68-2008 standard. In the structured experiment, the stab resistance property increased with the plate thickness and the angle. The addition of the CF to the materials mix improved the product stab resistance due to the improved mechanical properties of the product and a high aspect ratio. Laser sintered PA/CF with a plate thickness of 6.5 mm and a pyramid angle of 30°exhibited appeared to be the optimum composition for the desired application with area density of 6.58 kg/m^2. The total weight of the proposed SRBA would represent a 43% reduction of the weight of the conventional SRBA.

Acknowledgement

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