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Material selection on laser sintered stab resistance body armor

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Abstract

Stab resistant body armor (SRBA) is essential defensive equipment to protect the human body from injury due to stabbing. The conventional SRBAs are heavy and inflexible. Therefore a new type of SRBA has been recently developed using Laser Sintering (LS), which has resulted in a substantial improvement to SRBA in terms of structure and material design. In this development, carbon fiber was employed in the polyamide matrix to obtain the optimal stab resistant performances. Four kinds of materials were used and showed that the polyamide/carbon fiber (PA/CF) composite improved the stab resistance property compared to pure polyamide (PA). The stab resistance performances of flat plates were weaker than structured plates. The penetration depth of the PA/CF structured plate was 2 mm less than the pure PA structured plate. SEM observations of the products confirmed experimental conclusions that the addition of the CF largely improved the plate stab resistance. Moreover, using the PA/CF structured plate to produce SRBA would reduce the weight of the product by 30-40% comparing to the conventional SRBA, which would greatly reduce the physical burden to the wearer and largely improve the chance that the armor would be used.
Keywords: stab resistant, body armor, carbon fiber, polyamide

1.Introduction

The number of worldwide terrorist attacks has grown rapidly in the past few years. In China, gun ownership is strictly controlled, so that terrorist threats are based mainly on the use of knives. Stab resistance body armor has become an essential piece of equipment to protect people from knife injuries [1]. The protection layers of the SRBA are usually made of rigid panels (i.e. alumina, ceramic, etc.) or flexible panels (Kevlar fabric [2], UHMWPE fabric [3], etc). Body armor vests provide fully covered protection but at a cost: superfluous weight (3.5-4 kg), wearer discomfort, increased physiological demand, reduced mobility and contributions to back and other injuries [4-10].

Scientists and material designers have studied structural protection layers found in nature, in an attempt to mimic these natural approaches in the development of innovative body armor.

The first biological armor system can be traced back 540 million years to the Paleozoic era where dinosaurs evolved with body plates to protect their body cavities from sharp toothed predators [11]. In a similar manner many modern-day animals possess similar body armor, including mammals (e.g., armadillos and pangolin), reptiles (e.g. alligators, crocodiles, lizards) and numerous species of fish [12], which may offer new concepts for SRBA design. However, the hierarchical structure may cause difficulties in traditional manufacturing due to the design complexity and scale element intricacy.

Therefore, one solution to address these issues is in Additive Manufacturing (AM) technology. Laser Sintering (LS) is a typical AM technology that uses a laser to fuse polymer powder into a mass that has a desired three-dimensional shape. After one surface layer is laser scanned, a new layer of fresh powder is added on the powder bed, creating a new layer that is scanned. The process is repeated until the part is completed [13]. As a typical AM technology, LS has enabled the designers to design freely and realize highly innovative and geometrically complex textile-like functional assemblies.

Additive manufactured SRBA has been studied in recent years using LS technology. Johnson [14-15] 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 [16]. It was found that the armor manufactured using a 50:50 mixture of virgin and recycled powder performed much better than those fabricated from virgin powder. Based on this early success, a novel textile-like articulated, three-scale overlapping sample was fabricated with a maximum total thickness of 12 mm that exhibited a 1.6 mm penetration depth, which was far less than the 7 mm of the HOSDB limit. This reported research shows the potential promise of using LS technology to develop stab resistant body armor. However, 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) [17] requires that an acceptable personal body armor exhibit zero penetration when the stab impact energy is 24 J. Therefore, more work such as using new materials to produce lighter SRBAs is needed in the development of body armor.

In this paper, research was conducted to investigate the effect of carbon fiber on newly developed SRBA plates. Experiments were first conducted on four kinds of planar samples with different thicknesses to select the optimal materials and to estimate the proper thickness range; then a pyramid structure was designed and manufactured, the effects of angle and element size were compared and analyzed. Later, SEM observations were performed to study the micro structure in the laser sintered SRBA. This paper shows the first work to employ high-performance materials into the additive manufactured body armor, which identifies a new approach for the design, manufacturing and assembly of personal protective clothing design.

2. Methodology

2.1 Test method

All stab resistance tests of the novel armor materials adhered to the GA 68-2008 National Standard [17]. The test platform was comprised of a dropped hammer, a knife, test material and backing material (as shown in Fig. 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 tests should be performed with the ambient temperature of -20-55℃. The test apparatus used was purchased from Chengde Kecheng Testing Machine Co., LTD [18].

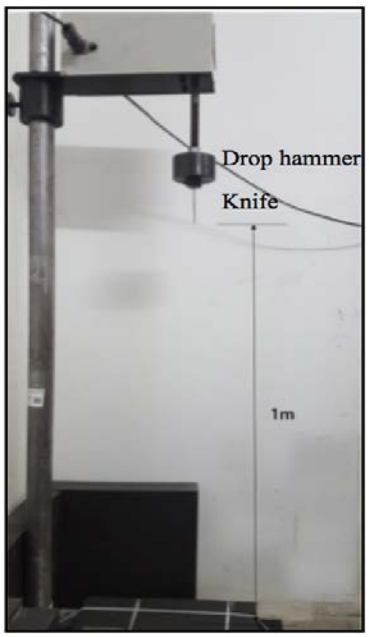


Figure 1. Stab resistance test platform

2.2 Material preparation

Four types of materials were employed for the LS fabrication: PA 3200, PA 4300, PA/GB and PA/CF. PA 3200 and PA 4300 were composed of pure polyamide powder with different polyamide 11 and 12 compositions. The PA/GF material was a composite comprised of 60 wt. % polyamide and 40 wt. % of glass fiber. The PA/CF was a composite comprised of 60 wt. % of polyamide and 40 wt. % carbon fiber. All of the samples were fabricated using a FARSOON 402

LS manufacturer, and were composed of a 50:50 mixture of virgin and recycled powder because it was found that the addition of the recycled powder improved the mechanical properties of the product. The mechanical properties of the four starting materials are listed in Table 1. All the samples were fabricated using SolidWorks software. For each preparation, sample plates were fabricated with dimensions of 60×60 mm as shown in Fig. 2(a). For the single layered specimens, the sample thicknesses were 9, 8, and 7 mm. For the double-layered specimens, the individual sample thicknesses were 1, 2, 3, 4, 5, 6, 7 mm and were packed with a thicker plate on the top to form a total thicknesses of 9 and 8 mm. For the multi-layered specimens, the sample thickness was 1 mm and the total thickness was 9 mm. Each sample fabrication experiment was repeated three times. The conditions for the sample preparation are shown in Table 2.

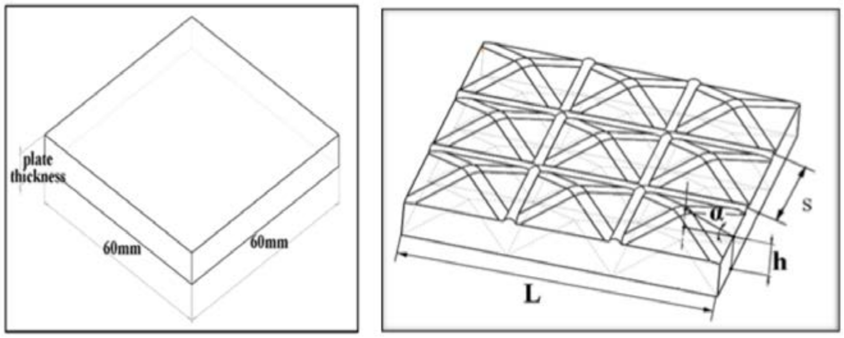
Table 1 Mechanical properties of four LS materials

Mechanical property	Unit	Material			
		PA 3200	PA4300	PA/GB	PA/CF
Product density	g/cm³	0.95	1.26	1.29	1.08
Tensile strength	Mpa	48.1	44	44	65-70
Elastic modulus	Mpa	1646	68	3500-7800	4700-6500
Bending modulus	Mpa	1431	2415	2415	4500-5600
Elongation	%	38	5	5	2-4

Table 2. Fabrication specifications for the preparation of flat samples.

Sample designations		Material			
		PA 3200	PA4300	PA/GF	PA/CF
Plate thickness (mm)	Single layered	9,8,7	9,8,7	9,8,7	9,8,7
	Double layered (top+bottom)	8+1, 7+2, 6+3, 3+6, 2+7, 1+8	8+1, 7+2, 6+3,3+6, 2+7, 1+8	8+1, 7+2, 6+3,3+6, 2+7, 1+8	8+1, 7+2, 6+3,3+6, 2+7, 1+8
	Multi-layered	1×9	1×9	1×9	1×9

To test the structure effect, the dimensions of the sample plates was set as 60×60 mm, which were fabricated from pure polyamide PA 3200 or the PA/CF composite. In each direction (x and y), three pyramids were placed. The dimension of the pyramid was 20×20 mm, which constituted 9 pyramids per plate. As shown in Fig. 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 ranged from 6.5, 7 and 7.5 mm, while the pyramid angle were 20, 25, 30° which was ~~accomplished~~ created via Solidworks 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. Fig. 3 shows an overview of the four types of specimens that were tested before the tests. As defined by the results listed in Table 1, samples with an area of 0.3 m^2 (GA 68-2008 Standard) and a thickness of 10 mm resulted in SRBAs with masses of 3.35, 4.28, 4.37, and 3.74 kg when composed of PA 3200, PA 4300, PA/GF or PA/CF.

The total weight was greater than the conventional SRBA, which may result produce too heavy a workload and heat stress to the wearer. Therefore, experiment on specimens thicker than 9 mm were not performed. The detailed experimental results are shown in Table 3. As shown, the laser sintered PA 4300 was not suitable for the stab resistance application, because all the experiments on this material failed. Based on the mechanical properties shown in Table 1, PA 4300 exhibited the highest bending modulus, indicating that this material was ductile.

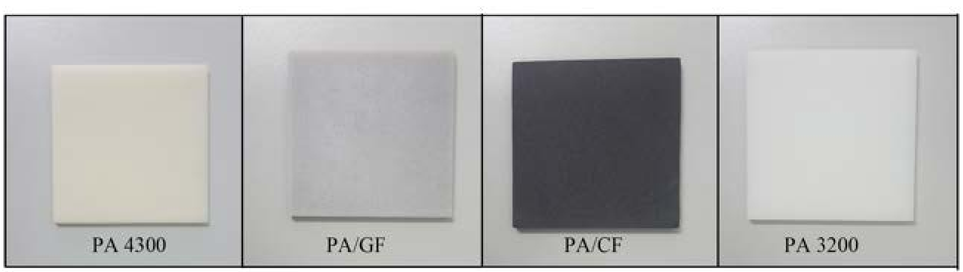
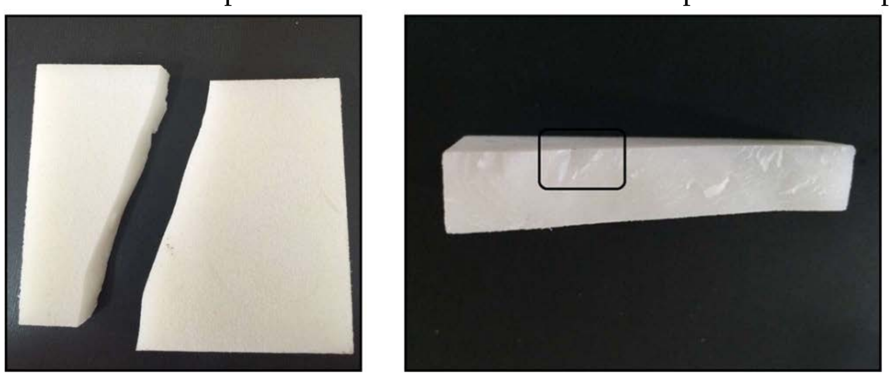


Figure 3 Overview of the four tested specimens before the **stab resistance** experiment, from left to right, laser sintered P4300, PA/GF, PA/CF, PA3200

Table 3 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(×) 8(×) 7(×)	9(×) 8(×) 7(×)	9(√) 8(√) 7(×)	9(√) 8(√) 7(×)
	Double layered (top+bottom)	8+1(×) 7+2(×) 6+3(×) 3+6(×) 2+7(×) 1+8 (×)	8+1(×) 7+2(×) 6+3(×) 3+6(×) 2+7(×) 1+8(×)	8+1(√) 7+2(√) 6+3(√) 3+6(×) 2+7(×) 1+8(×)	8+1(×) 7+2(×) 6+3(×) 3+6(×) 2+7(×) 1+8(×)
	Multi-layered	1×9(×)	1×9(×)	1×9(×)	1×9(×)

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. Fig. 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.



(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

Based on the results shown in Table 1, PA/GF was brittle and exhibited a high elastic modulus and bending modulus, which might produce low flexibility in the whole cloth assembly. Moreover, the PA/GF exhibited about 30% higher density than PA 3200 and PA/CF, which would produce a heavy physiological burden on the wearer. Therefore PA/GF was not an option for further consideration as a suitable material for the stab resistant body armor application.

It was assumed stacking of the 1-mm-thick plate might produce good penetration resistant properties as well as flexibility. However stacking of these materials proved to be unsuccessful, because all the specimens failed in testing. It was concluded from these planar experiments that PA/CF had potential for penetration resistant applications.

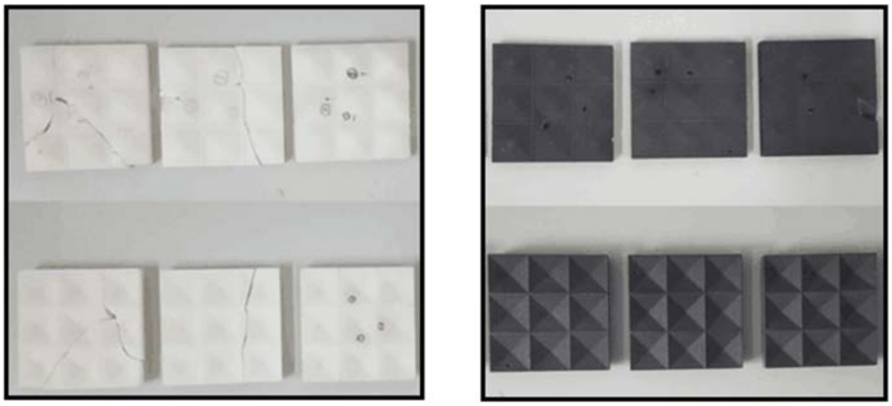
3.2 Structured plate

PA 3200 and PA/CF were selected as materials to use for further investigation of the structural effects for stab resistant performance. 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. For each group of samples, three experiments were performed from which the average penetration depth and standard deviation were obtained. It was determined that the penetration depth should be less than the plate thickness, the sample plate was not penetrated which was considered to be a success, otherwise the sample failed the test. The detailed experimental results are shown in Table 4. 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. Thicker plates and with 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°.

Table 4 Experimental results from the stab resistance experiments for two kinds of structured laser sintered materials. (Note: √: success; ×: failure.)

Material	Thickness (mm)	Penetration Depth (mm)		
		α=20°	α=25°	α=30°
PA 3200	6.5	12.6±1.3 (×)	11.9±0.8 (×)	9.7±2.0 (×)
	7	9.5±1.1 (×)	6.2±0.5(√)	6.4±0.7 (√)
	7.5	6.2±1.3 (√)	7.1±0.3(√)	6.7±0.5 (√)
PA/CF	6.5	5.6±0.3(√)	5.4±0.8(√)	5.9±3.3 (√)
	7	3.0±0.3(√)	4.1±0.2(√)	4.2±0.7(√)
	7.5	3.2±1.3 (√)	4.7±0.4(√)	4.2±0.3 (√)

Fig. 5 shows the front and back views of the structure of the laser sintered PA 3200 and PA/CF following the penetration tests. The specimens each 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 in tact with three small holes in each plate. No holes were observed at the back of the laser sintered PA/CF plates. The penetration depths of the laser sintered PA/CF obtained from Table 5 are about half that of the penetration depths in the laser sintered PA 3200, indicating that the addition of the CF increased the penetration resistance of the sample.



(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 by Scanning Electron Microscopy (SEM). Fig. 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 nanoparticles 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 [13].

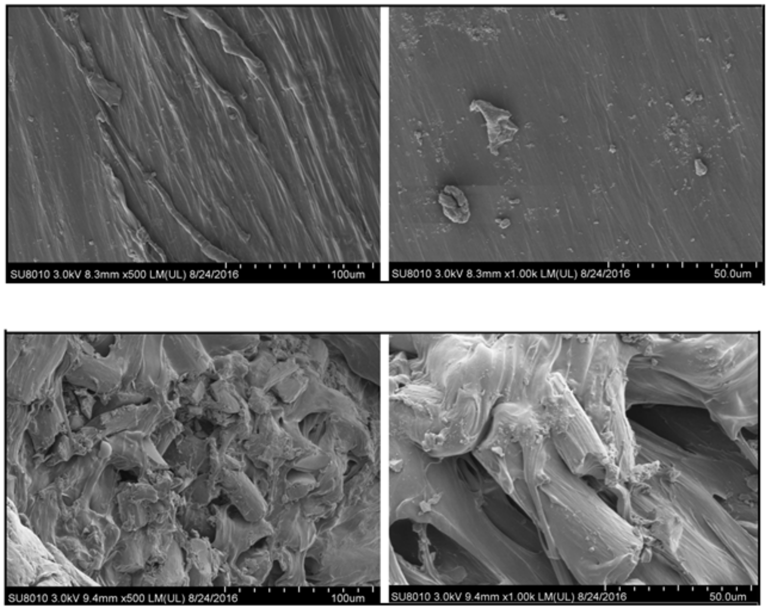


Figure 6: SEM images of the cross section of the structured specimen with a thickness of 7 mm and tilt angle of 20°, (a) laser sintered PA 3200 (top row), (b) laser sintered PA/CF (bottom row)

The area densities of the laser sintered plates were measured before the tests, as shown in Table 5. 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 if the protection area was 0.3 m^2 as required by the GA 68-2008 standard. This represented a 31- 37% less weight than the conventional SRBA. The area density increased with the thickness of the plates, because thicker plates produce more weight. The area density decreased with the pyramid angle increment for the laser sintered PA/CF, since the thickness of the inclined plane decreased with the increase of the tilt angle. The results were different for the laser sintered PA 3200 with a plate thicknesses of 6.5 and 7 mm, because of the errors that occurred during the fabrication process.

Table 5 Area density of the structured specimens (Note: ×: failure.)

Material	Thickness	Area density (kg/m^2)		
	(mm)	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(√)

4.Summary and Conclusions

In the study reported in this paper, natural armor found in various species of animals provided the inspiration for development of an advanced SRBA design. The Laser Sintering (LS) fabrication process was employed to produce the test samples because of the limitations imposed by conventional manufacturing methods and the complexity of the desired structure. Four kinds of LS materials were prepared and tested to determine their suitability for the knife stabbing protection based on the GA 68-2008 standard. A structured plate was designed and fabricated using Solidworks software and LS technology. The stab resistance property of the products was compared with a flat plate structure composed of the same starting materials. The optimum parameters for the proposed structure, including the tilt angle, plate thickness, and element size were tested and discussed.

It was concluded that PA 3200 and PA/CF were optimum materials for preparing a new armor for the desired stab resistant application. In the case of the planar experiment, a minimum thickness of 8 mm of planar laser sintered PA/CF or PA/GF was required to achieve a suitable penetration resistance to an impact energy of 24 J based on the GA 68-2008 standard. A double layered structure or multi-layered structure were not applicable in this penetration resistance application. Laser sintered PA/GF was not considered in this application, because the area density of the fabricated plate was too high. In the case of the structured experiment, a minimum thickness of 7 mm with pyramid angle of 25° in the laser sintered PA 3200 or a minimum thickness of 6.5 mm with a pyramid angle of 20° in the laser sintered PA/CF was required to meet the stab resistance requirement. The stab resistance property of the test materials 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. Considering the area density, the laser sintered PA/CF with a plate thickness of 6.5 mm and a ~~pryamid~~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.

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