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Investigations on laser sintered textiles for stab-resistant application

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Abstract

Stab resistance body armor (SRBA) is essential in protecting people from knife injuries. The protective parts of traditional SRBA are made of multi-layered ultra-high molecular weight polyethylene, which causes heavy heat stress for people wearing it. In this paper, the protective parts of SRBA were manufactured using laser sintering (LS) technology, which provide high manufacturing flexibility as well as high wearing comfort. Two different structures were investigated, one is squared plate and the other is pyramid. It was found the pyramid structure showed much higher stab resistance property then the plate, which is a result from the angle and thickness effects. This paper is the first effort applying the technology of LS and material of PA 3200 on SRBA, and by applying the pyramid structure on the protective layer of the SRBA, the total weight could reduce 30-40%.

Keywords: Stab resistance body armor, laser sintering, structure, pyramid.

1. Introduction

Body armor is the critical piece of protective equipment [1] nowadays for police officers, soldiers in the battlefield, and private security guards. Since ballistic attack is not very often in China due to the government control and restriction on carrying firearms, the threat from stabbing and other penetrating attacks from cold weapon is a major concern in public safety.

The protection layers of the SRBA are usually made of rigid panels (i.e. alumina, ceramic, etc.) or flexible panels (i.e. Kevlar fabric [2], UHMWPE fabric [3], etc). Body armor vest provides fully covered protections on the shoulder, stomach, chest and back, but at a cost: studies reported superfluous weight, wearer discomfort, increased physiological demand, reduced mobility and contributions to back and other injuries [4-9]. An average weight of stab-resistance body armor vest is 4 kg, which causes significant loading exhaustion on the policeman. Human wearing SRBA vest presented quicker heart rate, higher core and mean skin temperatures in 45 minutes with low intensity activities [10].

For centuries the animal bio-protection layers were studied to develop innovative body armors. 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. Zhu *et al.* [11] investigated on the puncture resistance of the scaled skin from striped bass, finding out the both individual and multiple scales provide a remarkable barrier against sharp puncture. Yang *et al.* [12] examined the scales from fish and mammals, concluded that the flexibility has been increased without significantly sacrificing strength by owning a hierarchical structure with collagen fibers joining more rigid units. John [13] studied five classifications of scales containing placoid, ganoid, osteoderms, elasmoid and the pangolin. 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 whiled minimizing back face deformation.

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 the additive manufacturing (AM) technology. Laser sintering (LS) is an 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 [14]. 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 stab resistance body was studied in recent years by using LS technology. Johnson [13] [15] firstly found the samples manufactured from 50:50 mixed of virgin and recycled powder performs much better than that from virgin powder, with a single layer maximum thickness of 5.6 mm and 11 mm to achieve the standard penetration limit when using PA 2200 and Duraform EX®. It was stated a thinner total layer thickness (9 mm) was achieved with a dual layered structure manufactured from Duraform EX®, of which with a thin top and a thick bottom. The research above shows great inspirations in using LS technology to develop stab resistance body armors. Regarding to the Stab Resistance Body Armor National Standard published by the Ministry of Public Security of the People's Republic of China in 2008 (GA 68-2008) [16], more investigation and analysis are required with the expectation of improved mechanical property and lighter weight, since in GA 68-2008 it is required zero penetration when the stab impact energy is 24 J. Moreover, taking the polymer density as 1.1 g/cm^3, the total body armor weight would exceed 3 kg if the plate thickness was beyond 10 mm, which may result to heavy workload and heat stress to the police when discharging duties.

In this paper, research was carried on laser sintered PA 3200 to meet the GA 68-2008 standard of stab resistance requirement. Experiments were first conducted on planar samples with different thicknesses to estimate the proper thickness range; a pyramid structure was designed and manufactured, the effects of angle and element size were compared and analyzed. This paper established a basis on laser sintered PA 3200 for stab resistance application, providing a new approach for personal protective clothing design, manufacturing and assembling.

2. Methodology

2.1 Test method

All stab resistance tests were followed the GA 68-2008 National Standard, which includes a dropping hammer tester, knife, test material and back material. The total mass of the dropping hammer and the knife is 2.4 kg, which would be released 1 m above from the test material in the vertical direction, free falling onto the test material accompanied with an impact energy of 24±0.5 J. It is required the qualified stab resistance body armor should not show any penetration after the tests.

The knife is made of 9Cr18Mo, which hardness is 50-55 HRC. It could only be used once to retain the test reliability. The size of the backing material is 400×400×67 mm, which constitutes of 4 layers of 6-mm-thick neoprene sponge, 1 layer of 30-mm-thick polyethylene plastic, and 2 layers of 6.5-mm-thick natural rubber from top to the bottom. All tests were be performed with the ambient temperature of 10-25 ℃. All apparatus were bought from CHENGDE KECHENG TESTING MACHINE CO., LTD [17].

2.2 Material preparation

All samples were manufactured using FARSOON 402 LS machine, and were made from 50:50 mixed virgin and recycled PA 3200 powder. The process parameters used and powder properties were summarized in Table 1. The dimensions of squared plates were 60×60 mm. In the single layered stab resistance experiment, specimens 1-4 with plate thicknesses 8, 9, 10, and 11 mm were tested. In the double-layered stab resistance experiment, specimens 5-10 were comprised of two laser sintered plates to generate a dual layered structure. The thicknesses of each plate are 1, 2, 8, and 9 mm respectively, which were manufactured twice. In the structured stab resistance experiment, the specimens were firstly created in the SolidWorks with the dimensions of pyramid structures were 20×20 mm, shown in Fig. 1. The size of the specimen is 60×60 mm. 5-mm-radius corners were added on the sides of the pyramids, and 2-mm-diameter semi-cylinders were attached on the space between the pyramids. The specimens were manufactured using different pyramid angles and plate thicknesses as shown in Table 2. Each experiment was repeated three times if the specimen was not broken.

Table 1: FARSOON 402 LS machine process parameters and PA 3200 properties.

LS machine process parameters			Material property	
Layer thickness	0.1 mm		Product density	0.95 g/cm^3

Chamber operation temperature	170 ℃		Tensile strength	48.1 Mpa
Cooling down temperature	120 ℃		Elastic modulus	1646 Mpa
Laser scan power	15 W		Elongation	38 %
Laser scan speed	1m/s		Bending modulus	1431 Mpa

Table 2: Double layered (left) and structured (right) specimen specifications.

Specimen number	Plate thickness (mm)			Specimen number	Pyramid angle (°)	Plate thickness (mm)
	Top + Bottom	Total		11-16	20	6.5,6.75, 7, 7.25, 7.5, 8
5-6	1+9, 9+1	10		17-22	25	6.5,6.75, 7, 7.25, 7.5, 8
7-8	2+8, 8+2	10		23-28	30	6.5,6.75, 7, 7.25, 7.5, 8
9-10	3+7, 7+3	10		29-34	35	6.5,6.75, 7, 7.25, 7.5, 8

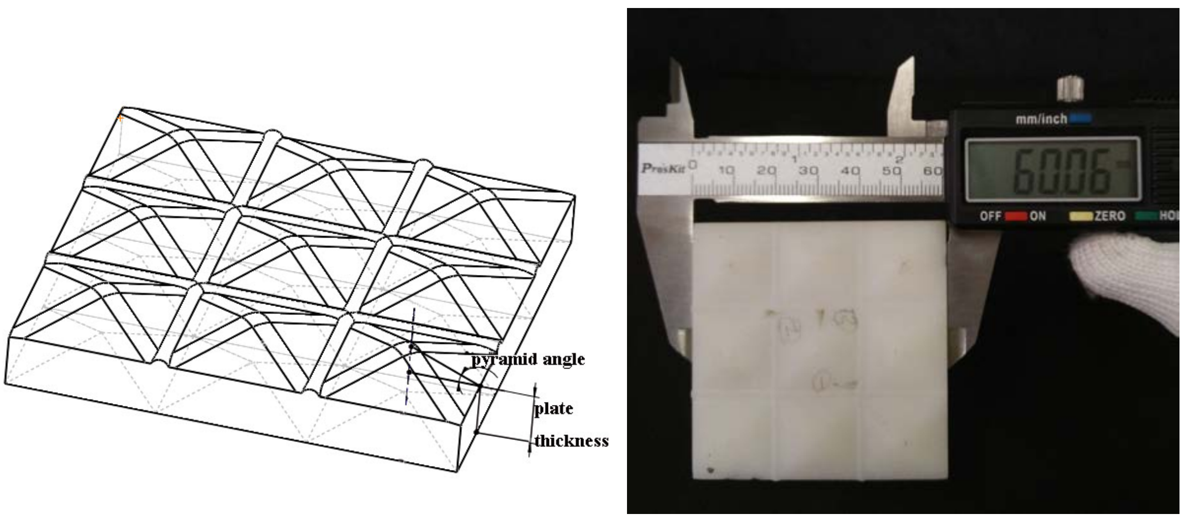

Figure 1：Pyramid structure plate: structure drawn from the SOLIDWORKS (left), laser sintered plate with dimensions of 6.006 mm after the experiment (right).

3. Results and Discussion

3.1 Squared plate experiment

Experiments were performed on the single layered and double layered specimens. However all specimens were broke during the experiment. Fig.2 shows a picture of the 11-mm-thick specimen after the test, which was broken into two pieces. The red square highlighted the notch area where the blade stroked on. Taking the polymer density as 0.95 g/cm^3 and a protection area of 0.3 m^2 as required by the GA 68-2008 Standard, the total body armor weight would exceed 3 kg if the plate thickness was beyond 11 mm, which may result to heavy workload and heat stress to human. So experiment on thicker plate was not performed. It is concluded that the laser sintered pure PA 3200 of squared plate is not stab resistance enough to meet the demand.

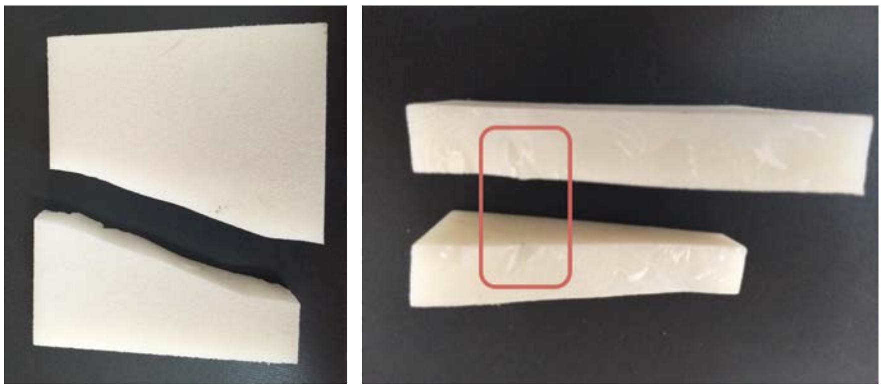

Figure 2: 11-mm-thick laser sintered PA 3200 after the stab resistance experiment: front view (left); cross section view (right).

3.2 Structured plate experiment

Experiments were conducted with specimens featured by pyramids of varied angles and plate thickness. The pyramid angle is measured between the ground and the tilted pyramid ridge, and the thickness is measured on the corner of the plate, shown in Fig. 1. Fig. 3 shows the stab resistance test results of the structured specimens. When the pyramid angle is 20°, specimens with plate thicknesses 6.5, 6.75 and 7 mm all failed the test, of which the averaged penetration depths are 6.1, 4.9 and 2.5mm. Fig. 4 shows the experimental results for the plate with plate thickness of 6.75 mm and angle of 20°. Specimens with plate thicknesses of 7.25, 7.5, 7.8 and 8 mm all passed the test. When the plate thickness is 7.25mm, the penetration depth is 0.5mm, however the hit happened on the top of the pyramid, which could not reach the bottom of the plate, so the test is regarded as a success. Blades were stabbed into the rest of the plates with average depths of 5.1, 7.4, and 5.4 mm separately. The area densities were 7.9, 8.3, and 8.4 kg/m^2. Thicker plate indicates stronger pyramid structure, but at a cost: the overall weight of the protection layer would easily beyond 3 kg, which is relatively high for the SRBA application.

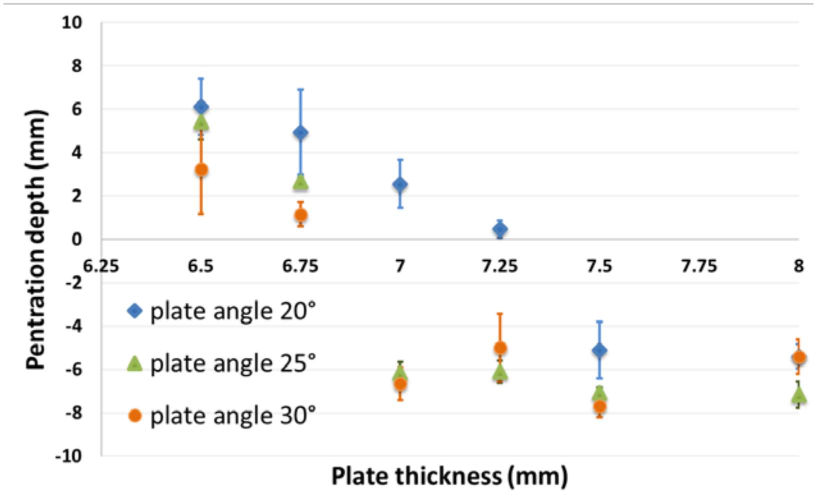

Figure 3: Penetration depths of the pyramid structured plates with different angel and thickness (the negative value indicates the stabbing depth, i.e., the experiment is a success; the positive value indicates the penetration depth, i.e., the experiment is a failure.)

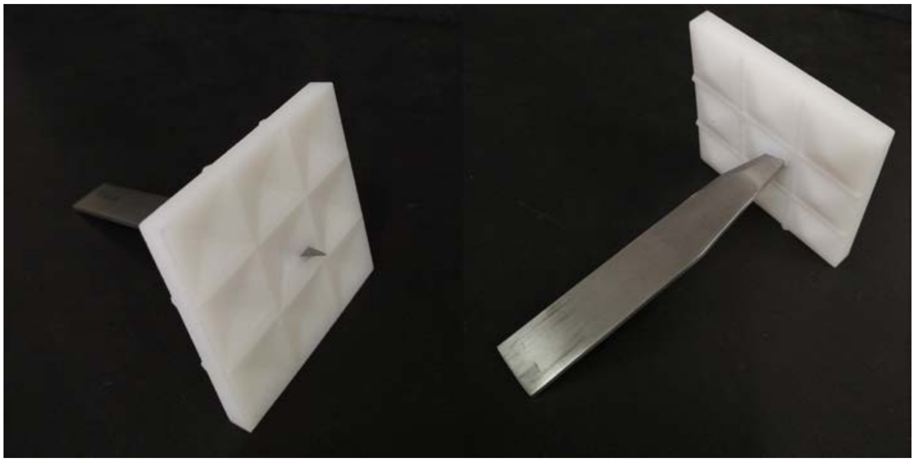

Figure 4: The experimental results of the pyramid structured plates with pyramid angle of 20° and plate thickness of 6.8mm.

When the pyramid angle is 25°, specimens with plate thicknesses of 6.5 and 6.75 mm failed the test, while the ones with thicknesses of 7, 7.25, 7.5, and 8 mm passed. The former ones were penetrated with 5.4 and 2.65mm during the test, indicating poor stab resistance. The later ones showed averaged stabbing depths of 6.2, 6.1, 7.1 and 7.2 mm, respectively. The area densities of the specimens with plate thickness of 7 and 7.25mm are 7.3 and 7.5 kg/m^2, which means the weight of the protection layer would be lower than 2.25 kg in consideration of the protective area of body armor is 0.3 m^2.

The experimental results of the plates with the pyramid angle is 30°are similar to the plates with the angle 25°: The minimum thickness for the successful experiment is 7mm. The penetration depths are 3.2 and 1.2 mm respectively when the plate thicknesses are 6.5 and 6.75 mm. The knives stab into the plates 6.7, 5.0, 7.7, and 5.4 mm separately when the palte thicknesses are 7, 7.25, 7.5 and 8mm.

The experiments were failed when the pyramid angle is 35°and the plate thickness ranges from 6.5 to 8mm. The penetration depths were not available since the plates were broken into pieces.

It is shown the penetration depth decreases with the increasing plate thickness, when the pyramid angle is constant; nevertheless the plate thickness did not affect the stab depth too much when the plate is strong enough to stand the knives stabbing, with a random stabbing depth of 5.5-7mm. It could be concluded that the stab resistant property increases with the increasing plate thickness to an extent, i.e., plate thickness is less then 7-7.25 mm.

Figure 5： Experimental results of 7-mm-thick pyramid structured plates when the pyramid angles are 20°, 25°, 30°and 35° from left to the right (upside: the front view; downside: the back view).

The plate stab resistance property increases then decreases with the pyramid angle increment. For example, the penetration depth decreases with the increasing pyramid angle (20°to 30°) when the plate thickness is 6.5 or 6.75 mm, which indicates an enhancement of the stab-resistance property. However when the pyramid angle increases to 35°, the plate was broken into pieces with an estimated penetration depth of 50 mm. The experimental results of the 7-mm-thick plates are shown in Fig. 5, the plates were not broken when the pyramid angles are 25° and 30°, with the penetration depths of 6.2 and 6.7 mm. The plates were broken when the pyramid angles are 20° and 35°. The experimental results of the 7.25-mm-thick plate are quite similar to the results above. Thus it is concluded the plate has improved stab-resist properties when the pyramid angles are 25° and 30°. The phenomena could be explained as the tilted angle helps disperse the stabbing force to an extent, however the larger angle leads to a thinner pyramid thickness due to the characteristics of the SOLIDWORKS drawing, which results in weaker stab resistance properties.

Table 3 shows the experimental results for the pyramid-structured plates with different pyramid angles and plates. It could be found that the 7 mm is the minimum plate thickness and 30°is the maximum pyramid angle for a successful experiment. The plates with thinner thickness less than 7 mm or wider pyramid angle larger than 30°could not survive from the stabbing test. Taken the plate area density into consideration, which is effected by the plate thickness, the optimal design is the plate with thickness of 7 mm and pyramid angle of 25°, of which the area density is 7.27 kg/m^2.

Table 3: Results of the stab-resistance tests ("√": pass the test, "×": fail the test)

Thickness / angel	6.5	6.75	7	7.25	7.5	8
20°	×	×	×	√	√	√
25°	×	×	√	√	√	√
30°	×	×	√	√	√	√
35°	×	×	×	×	×	×

4. Summary and Conclusions

In this paper, the pyramid structured stab-resistance plate was designed based on bionics theory, manufactured using LS technology, tested under the National Standard GA68-2008, and proofed to be a great design in the stab resistance experiments. The plain plates which thicknesses are 10 mm (dual structure) or 11 mm (single layer) could not survive from the experiment, however the pyramid-structured plate managed the experiment when the plate thickness is 7 mm and the pyramid angle ranges from 25°to 30°. It was founded the plate stab resistance property increases with the plate thickness to an extent. The plate thickness does not affect too much on the stabbing depth when it goes beyond 7.5 mm when the pyramid angle is appropriate. Meanwhile, the stab resistance property of the pyramid structured plate increases then decreases with the plate thickness increment, i.e., the plates with angles of 25°and 30°shows enhanced stab resistance property than the ones with angles of 20°and 35°. It is concluded the optimal design for the pyramid structured plate is the one with plate thickness of 7 mm and pyramid angle of 25°, which established great stab resistance property as well as relative low area density.

References

1. Xiaogang Chen, Dan Yang. Use of 3D angle-interlock woven fabric for seamless female body armor: Part 1: Ballistic evaluation. Textile research journal. 2010; 80(15): 1581–1588.

2. Floria Eve Clements. Development of flexible puncture resistant materials system using silica nanoparticles. Master thesis. 2007; Florida Atlantic University.

3. Chang-sheng Li, Xian-cong Huang, Yan Li, Nianci Yang, Zhihao Shen and Xing-he Fan. Stab resistance of UHMWPE fiber composites impregnated with thermoplastics. Polymers for advanced technologies. 2014; (25): 1014-1019.

4. Dempsey P, Handcock P, Rehrer N. Impact of police body armour and equipment on mobility. Applied Ergonomics. 2013; 44: 957–961.

5. Hooper R H. Why do police officers leave their body armour in the cupboard? In M. A. Hanson, E. J. Lovesey, & S. A. Robertson (Eds.). Contemporary Ergonomics. 1999; 358–362.

6. Larsen B, Netto K, Aisbett B. The effect of body armor on performance, thermal stress, and exertion: A critical review. Military Medicine. 2011; 176: 1265–1273.

7. Ricciardi R, Deuster P, Talbot L. Metabolic demands of body armor on physical performance in simulated conditions. Military Medicine. 2008; 173: 817–824.

8. Stubbs D, David G, Woods V, Beards S. Problems associated with police equipment carriage with body armour, including driving. Contemporary Ergonomics. 2008; 153: 23–28.

9. Paddy C Dempsey, Phil J Handcock, Nancy J Rehrer. Body armor: the effect of load, exercise and distraction on landing forces. Journal of Sports Science. 2014; 32 (4): 301-306.

10. Andrew J Pyke, Joseph T Costello, Ian B Stewart. Heat strain evaluation of overt and covert body armour in a hot and humid environment. Applied Ergonomics. 2015; 47: 11-15.

11. Deju Zhu, Lawrence Szewciw, Franck Vernerey, Francois Barthelat. Puncture resistance of the scaled skin from striped bass: Collective mechanisms and inspiration for new flexible armor designs. Journal of the mechanical behavior of biomedical materials. 2013; 24: 30-40.

12. Wen Yang, Irene H Chen, Bernd Gludovatz, Elizabeth A Zimmermann, Robert O Ritchie and

Marc A Meyers. Natural Flexible Dermal Armor. Advanced Materials. 2013; 25: 31–48.

13. Andrew Allan Johnson. Establishing design characteristics for the development of stab resistant Laser Sintered body armour. Doctoral thesis. 2014; Loughborough Design School, Loughborough University, UK.

14. M Yuan, T Diller, D Bourell. Thermal Conductivity Measurements of Polyamide 12. Solid Freeform Fabrication Symposium Proceeding. 2011; 427-437, Austin, TX.

15. Andrew Johnson, Guy A. Bingham, David I Wimpenny. Additive manufactured textiles for high-performance stab resistant applications. Rapid Prototyping Journal. 2013; 19(3): 199-207.

16. Stab resistnace body armor for police. People's Republic of China Public Safety National Standard. GA 68-2008. Ministry of Public Security of the People's Republic of China.

17. CHENGDE KECHENG TESTING MACHINE CO., LTD, http://www.kcsyj.com/main/index.asp. Available on 2015/8/28.