EFFECT OF STRUCTURE ON DYNAMICAL STAB-RESISTANCE BEHAVIORS OF LAMINATES COMPOSITE

by

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The dynamic stab-resistance behaviors of laminate composites composed of TA15, TA1 titanium with various thicknesses of ultra-high-molecular-weight polyethylene, and polyester fabrics are characterized under dynamic stab testing conditions and analyzed by a new method using the average velocity of tension-compaction-plastic deformation process to calculate the ratio of energy in different damage process. The damaged area is observed by optical microscopy and SEM, and the impact force-time curve and damage degree are analyzed, and the energy of different processes during the dynamic stab test is calculated. The results show that laminates with the structure of high strength material among the low strength materials have much better performance than other specimens.

Key word: *laminates, stab-resistant behaviors, impact force, damage area*

Introduction

The conventional stab-resistance body armors fabricated by metals [1, 2] or high-performance fibers [3-5] exhibit good stab resistance properties, but the drawbacks of metal body armors are uncomfortable to wear due to the weight, poor flexibility, poor heat, and poor vapor permeability, on the other hand, the body armors comprised of many layers of high-performance fibers are also so heavy that the agility and mobility are not allowed for the wearers, and sometimes fatalities are arisen [6]. In the process of a knife's impacting a soft armor comprised of different high-performance fibers, it was revealed that the surface hardness and shear strength were the key mechanical properties that affected the overall stab-resistance performance [4]. With this in mind, the material selection and design process of the composite laminates for stab resistance are important factors to optimize the armor. For better performance, the structural design of laminates has been noticed, such as sandwich structure, which consists of metal and fiber. Other soft materials [7-10] are also used as the energy absorption component in an impact protection system in recent years. Another structure is the egg-shell form, which exhibits excellent specific strength [11]. In the sandwich structure, the metal plate plays a major role in determining stab-resistant property, weight reduction and protection level improvement. In order to show the influence of material selection and structure on protective systems, different kinds of ceramic layer [12, 13], aluminum layer inserts [14, 15] were used to enhance the strength of the laminates composite. It means that mechanically different materials should be used to in the body armor systems to meet the needs of a high degree of stab-resistant vests, such as the combination of ceramic or metal plate inserts

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and fabrics. In addition, the stacking order and the mechanical properties of the constituent materials in laminates are related to the failure mode in the through-thickness direction. Clearly, with these results in mind, there is a need for the effect of the material selection and design process on the stab-resistance property of laminates composite. In this paper, an effort has been made in investigating the effect of the mechanical properties of metal inserts and stacking order on the dynamic stab-resistant performance of laminates composite, analyzing the impact force during stab process and damage mechanisms after stab test to understand the dependent factors in stab resistance improvement.

Experimental details

Materials

In order to investigate the effect of structure on dynamic stab resistance properties of laminates comprised of different materials, plain woven ultra-high-molecular-weight polyethylene (UHMWPE) and polyester fabric with an areal density of 240 g/m^2 were used as soft material to play the role of buffering, and TA15, TA1 sheet of 0.5 mm thickness were used as high strength material to resist the cutting from the knife in the research. The mechanical property of titanium used in the test is shown in tab. 1. The chemical composition of TA15 and TA1 are Ti-6.5Al-2Zr-1Mo-1V (wt.%) and Ti-0.20Fe-0.18O (wt.%), respectively.

The laminates of TA15/UHMWPE, TA1/UHMWPE, TA15/polyester, and TA1/polyester are composed of titanium (TA15 or TA1) of 0.5 mm thickness and 20, 30, 40, and 50 layers of fabrics (UHMWPE or polyester). The UHMWPE and polyester fabrics of different layers were folded and sewed as an equilateral triangle with a diameter of 75 mm in the inscribed circle. The TA15 and TA1 sheet of 0.5 mm were machined into a circle with a diameter of 75 mm for the stabbing test. In the test, folded and sewed fabrics were clamped with titanium on the instrument as a specimen for the dynamic stab test. The laminate specimens are shown in tab. 2. Moreover, the neat UHMWPE and polyester laminates specimens of different layers were prepared as a contrast.

Table 1. Mechanical properties of titanium

Titanium	Tensile strength [Mpa]	Yield strength [MPa]	Elongation [%]
TA1	386	280	42%
TA15	1080	915	20%

Table 2. Laminates structure

Structure	Sign*	Up	Middle	Down
A	T/F	One TA1 or TA15 of 0.5 mm thickness	–	30/40/50 layers polyester or UHMWPE
B	F/T	30/40/50 layers polyester or UHMWPE	–	One TA1 or TA15 of 0.5 mm thickness
C	F/T/F	15/20/25 layers polyester or UHMWPE	TA1 or TA15 of 0.5 mm thickness	15/20/25 layers polyester or UHMWPE

* T is titanium, F is fabrics

Experimental apparatus

The tests specimens of laminates were stabbed by a knife directly on the circular jaws of the instrument, the circular jaws have inner and outer diameters of 70 mm and 80 mm, respectively. The apparatus drops freely under its own weight to strike the specimens, which consists of an engineered knife blade on the drop mass with a total weight of 2.49 kg. The impactor is S1 knife based on the National Institute of Justice Standard 0115.00 as shown in fig. 1.

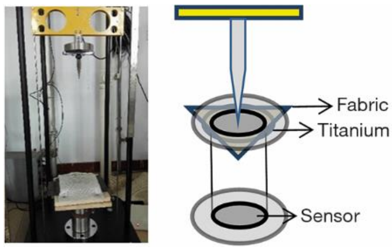

Figure 1. Schematic and instrument for dynamic stab test

The knife impacted the laminate specimens at a speed of free-falling movement. In order to reach the impact energy of 24 J, the drop height was set 0.98 m for each specimen. In the test, the impact data of energy and displacement during the process of stab was recorded by the sensors connected with the computer. The sensor is under the circular jaws in order to record the impact force received by the specimens. The apparatus is shown in fig. 1. After the test, the damaged area of laminates was observed by OM and SEM, and the energy data were analyzed.

Results and discussion

The effect of mechanical properties of component materials on the stab resistance of composite laminates

In order to investigate the effect of mechanical properties of component material on the structure of laminate in the test, 0.5 mm TA15 and TA1 alloy sheets are selected with different properties of strength and plasticity as shown in tab. 1. It can be seen that the strength of TA15 alloy is higher than that of TA1, but the elongation of TA1 sheet is prominent. The stab-resistant behaviors of neat polyester fabrics of different layers are shown in fig. 2(a). It can be seen that the peak impact forces increase with the increase of thickness of polyesters, and the shortest time with the max peak force of 1800 N is observed in 50 layers ones because of the effective prevention from specimens to the knife. It can be deduced that the shorter time and larger peak force correspond to better stab-resistance property of materials, and the longer time is related with the large displacement and touch area between knife and specimens. The stab-resistant behaviors of P/TA1 and P/TA15 are shown in figs. 2(b)-2(d). According to the shape of curves, it can be divided into two processes by the peak impact force, the rising curve before peak impact force is related to the process of tension and compaction in polyester, plastic deformation in titanium, along with the emergence of the unstable crack, but damage failure occurred in laminates presented as the decreasing curve after peak impact force. It can be seen that the obvious fluctuation in the flow curve after peak impact force gradually faded out with the increase of thickness of polyesters, so the peak impact force is the ending of the process of tension-compaction in polyester, plastic deformation in titanium alloy, as well as the start of the emergence of the unstable crack and the start of the process of crack propagation steadily in the specimens. The drop tower stab performance of the TA15/polyester, TA1/polyester targets against the knife impactor are shown in figs. 2(b)-2(d), it can be seen that all the peak impact forces increase with the increase of thickness of polyesters, and P/TA1 laminates exhibit larger peak impact force than P/TA15 of same thickness because of the excellent plasticity of TA1.

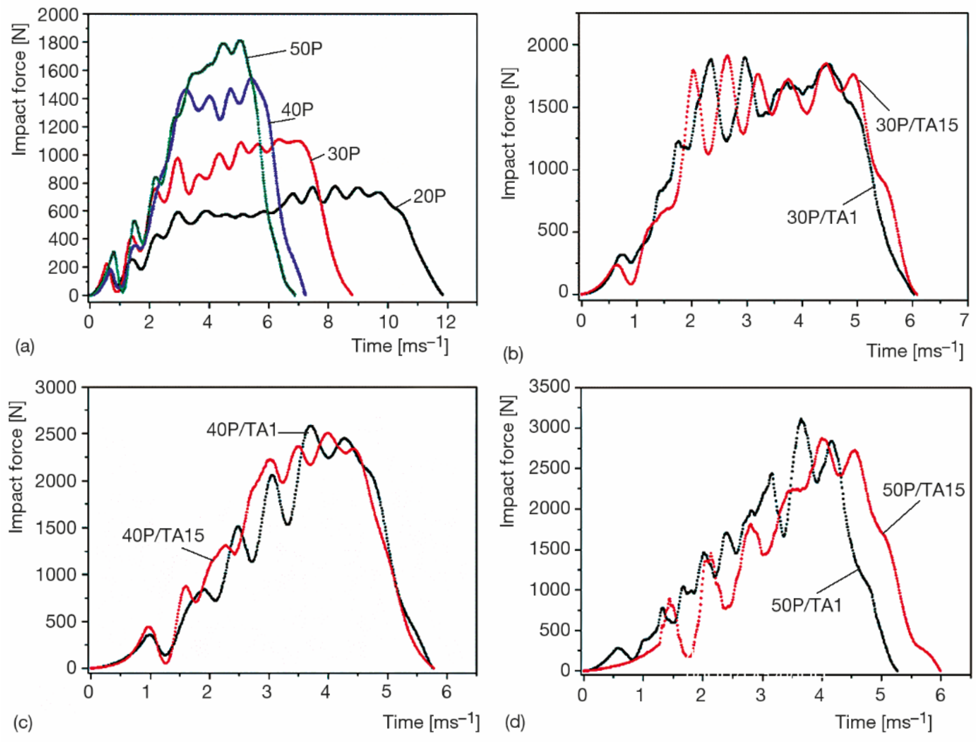

Figure 2. The dynamic stab resistant behavior of different laminates; (a) neat polyester of different layers, (b) 30 layers of polyester and titanium, (c) 40 layers of polyester and titanium, and (d) 50 layers of polyester and titanium

Figure 3 shows the damaged area of the first layer of polyester and the bottom of titanium in 40 layers P/TA1 and P/TA15 laminates. It can be seen that the damaged area of 40P/TA1 mainly shows the tension of polyester fiber and obvious plastic deformation in TA1 with a small damaged area of about 1941 μm of diameter. It means that the long process of compaction in polyester and large plastic deformation in TA1 is caused by the impact energy. However, cutting off fibers in polyester and large fractures of about 9257 μm of diameter in TA15 can be observed in laminates of 40P/TA15. In addition, the dynamic stab-resistant behaviors of 30 layers P/TA1 and P/TA15 laminates all show two peaks of impact force at an earlier time of about 1.7-3 ms (the instantaneous time was calculated after the knife touch the fabrics during the test), and the two peaks of TA15 appear earlier at time of 1.7 ms and 2.0 ms separately. It means that the dominant role of stab resistance in laminates is the plastic deformation and damage propagation of TA1 and TA15, especially the effect of large inflexibility shown by TA15 because of the low plasticity. In addition, the curve shape of P/TA1 and P/TA15 laminates of 40 layers and 50 layers of polyester are similar to that of neat polyester with only one peak of impact force because the dominant mechanism of stab resistance in laminates are the process of compaction, tension, and cutting of polyester and the effect of the inflexibility of titanium are reduced by the increasing of polyester layers.

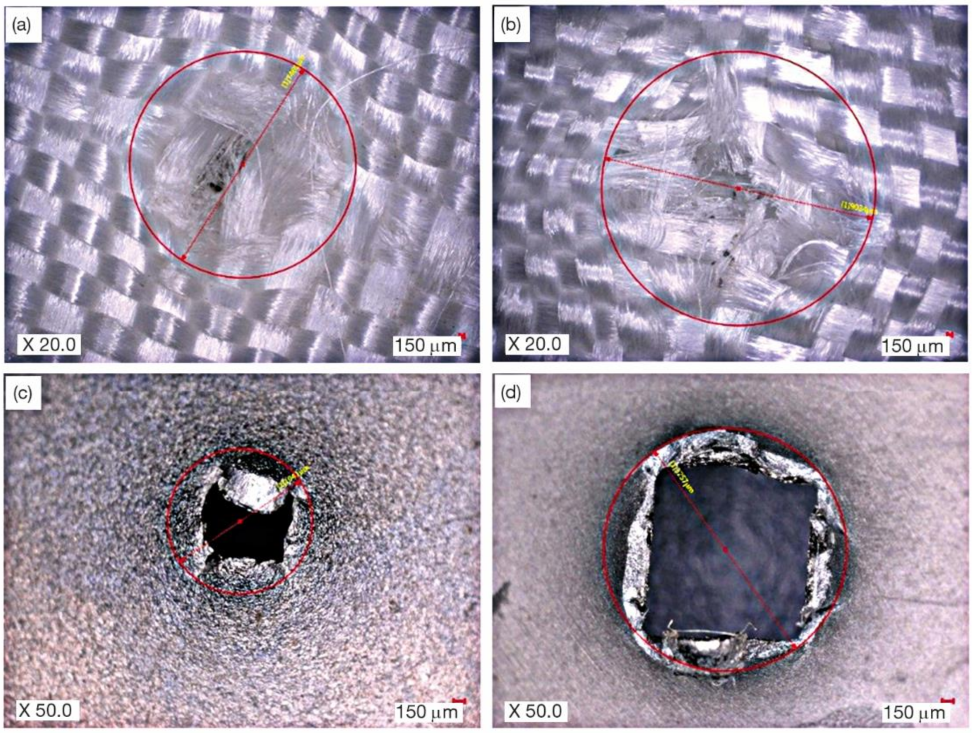

Figure 3. The damaged area of laminates; (a) the first layer of polyester in 40P/TA1, (b) the first layer of polyester in 40P/TA15, (c) TA1 at the bottom of 40P/TA1, and (d) TA15 at the bottom of 40P/TA15

The effect of stacking order on the stab resistance of composite laminates

The impact force of laminates with different structures against the knife impactor during the dynamic stab test is shown in fig. 4. It can be seen that the curves of F/T show the max peak impact force in the three structures of laminates. It is related to the long process of tension, compaction, and cutting that occurred in fabrics, and plastic deformation occurred in titanium before arrived the peak impact force, especially the laminates with the structure of F/T/F exhibit fluctuate as shown in the curves.

In order to analyze the damage mechanisms of different structures, the energy absorbed in different processes is calculated. In the process of calculation, the initial velocity, v_i, is 4.42 m/s which is decided by the drop height. Meanwhile, the velocity when impact force arrived at the peak in the curve is defined as v_p, and the instantaneous velocity of the ending of impact is 0 m/s defined as v_e, then the energy of E1 absorbed in the process of compaction in polyester and plastic deformation in Titanium and the energy of E2 absorbed in the process of crack propagation steadily are calculated respectively.

$$E1 = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_p^2 \tag{1}$$

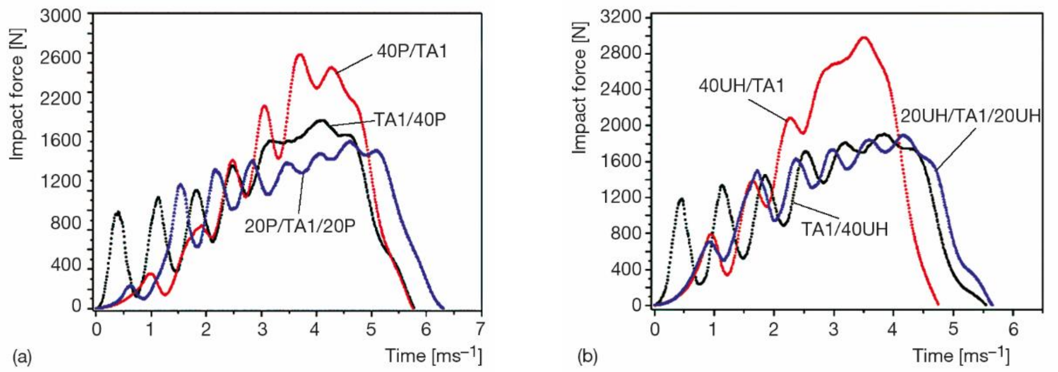

Figure 4. The dynamic stab-resistant behaviors of laminates with different structures; (a) TA1 and polyester of 40 layers and (b) TA1 and UHMWPE of 40 layers

$$E2=\frac{1}{2}mv_{\mathrm{p}}^{2}-\frac{1}{2}mv_{\mathrm{e}}^{2}=\frac{1}{2}mv_{\mathrm{p}}^{2}-0 \tag{2}$$

Then the ratio of energy E1 to E2 should be:

$$\frac{\frac{1}{2}mv_{\mathrm{i}}^{2}-\frac{1}{2}mv_{\mathrm{p}}^{2}}{\frac{1}{2}mv_{\mathrm{p}}^{2}-0}=\left(\frac{4.42}{v_{\mathrm{p}}}\right)^{2}-1 \tag{3}$$

It can be deduced that the more energy of E1 absorbed in the process of compaction in polyester and plastic deformation in Titanium, the less energy of E2 absorbed in the process of crack propagation steadily according to the law of energy conservation. It can be deduced that the v_{p} of the peak force would be low when E1 is large, because v_{p} is inverse proportion to E1. It is known that v_{p} is hard to record, so the average velocity $\bar{v}_1$ of tension-compaction-plastic deformation process and the average velocity $\bar{v}_2$ of crack propagation steadily process can be used to reflect the change of v_{p}.

$$\frac{\bar{v}_1}{\bar{v}_2}=\frac{m4.42-v_{\mathrm{p}}}{m(v_{\mathrm{p}}-0)}=\frac{\int_{0}^{t1}f1\Delta t1}{\int_{t1}^{t2}f2\Delta t2} \tag{4}$$

The integral area ratio of different structures is shown in tab. 3. It can be seen that the structure of P/TA1/P in different thickness laminates exhibits the max value of v_1/v_2, and the structure of P/TA1 shows the minimum value of v_1/v_2. It means that in the structure of P/TA1/P, the more energy of E1 absorbed in the process of compaction in polyester and plastic deformation in Titanium, the less energy of E2 absorbed in the process of crack propagation steadily. The reason is that the strength material TA1 located in the middle of the structure is benefit to the fabrics located on the top of the structure to occur the process of tension-compaction effectively by playing the role of plastic deformation completely to resist the cutting of knife, simultaneously contribute to the fabrics which located under the structure play the role of resistance to impact force by the tension of fiber. Finally, in order to verify the laminates with the structure of high strength material being the middle of the low strength materials should show better performance, the fabrics of different properties are used in stab test. The dynamic stab-resistant behavior and damage morphology of laminates constituted by polyester and UH are shown in fig. 5. In the laminates, UHMWPE is used as the strong material, and polyester is used as soft material. It can be seen that the damaged area of the last layer in the structure of 10P/10UH/10P/10UH is a light bump of 1311 μm. The damaged area in the structure of 20UH/20P is the tension of fiber mainly, but many cutting of fiber can be observed obviously in the damaged area of 20P/20UH structure.

Table. 3 The Integral area ratio before and after the maximum impact force

Structure	30P and TA1	40P and TA1	50P and TA1
TA1/P	1.178321678	2.461077844	2.636363636
P/TA1	0.964169381	1.796116505	2.25308642
P/TA1/P	2.210280374	2.711764706	3.177304965

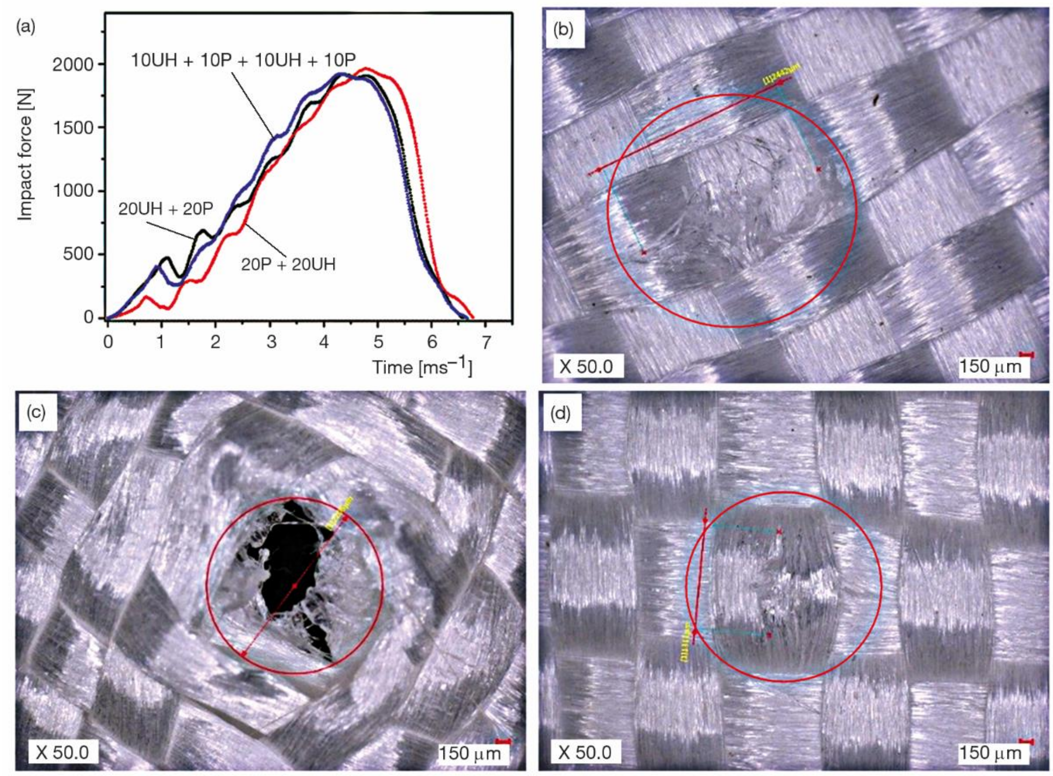

Figure 5. The dynamic stab-resistant behavior and the damage degree of UHMWPE and polyester of 20 layers; (a) the dynamic stab-resistant behavior of three structures, (b) damage degree of the last layer in the laminate of 20UH/20P, (c) 20P/20UH, and (d) 10UH/10P/10UH/10P

As mentioned previously, it is obvious that the performance of laminates during the dynamic stab test against knife threat can be effectively improved by controlling the structure, and the specimens with proper laminated order show a stronger capability to absorb the impact force by strength the process of tension-compaction in polyester and plastic deformation in titanium but lower the process of crack propagation steadily.

Discussion and conclusions

The displacement during the process of stab is an important factor affecting the stab-resistance behavior, similar to bond stress-slip model in a porous concrete [16], a stress-slip relationship of the stab process should be established in future.

The drop-weight tests of composite laminates with different structures against knife threats were performed to investigate the effect of mechanical properties of component materials and to stack order on the stab resistance of composite laminates. The laminates with a structure of high strength material being the middle of the low strength materials show much better performance than other specimens, and the impact force-time curve and damage degree show that the effect of structure on laminates is related to the damage mechanism. The curves of dynamic stab resistance can be divided into two processes by the peak impact force, the rising curve before peak impact force is related to the process of tension and compaction in polyester, plastic deformation in titanium, along with the emergence of the unstable crack, but damage failure occurs in laminates presented as the decreasing curve after peak impact force.

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