IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 2 March 2023, accepted 8 May 2023, date of publication 15 May 2023, date of current version 30 May 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3276643

RESEARCH ARTICLE

The Material Chosen Methods Base on AUTODYN Dynamic for Substrate Film of Flexible Film Sensor Circuit

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The research of this article's financial support was supported by the National Natural Science Foundation of China 2021(grant 51477181). The total amount used to support this research is about 200k CNY. An important part of the research supported by the Foundation is to research and find the cheapest and most efficient polymer material that can be used to be flexible film sensor substrates.

ABSTRACT In the process of ammunition test & evaluation, to accurately evaluate the lethality of personnel targets on the battlefield, it is necessary to accurately measure the velocity and coordinates of ammunition fragments. At present, the most effective method for measuring the projectile velocity and the midpoint coordinates of ammunition is to use the measuring circuit printed with silver paste on the flexible substrate material. Considering that the physical properties of the substrate material will greatly affect the velocity attenuation value of the fragments and the size of the hole at the hitting position, this article mainly uses the AUTODYN software to simulate the process of the projectile penetrating three kinds of polymer materials and copper circuit which are used in many universities and test ground and selects the suitable polymer material that has the least negative effects on the velocity of the projectile, The speed measurement accuracy of the flexible silver paste printing film sensors circuit printed on three different polymer substrate materials is compared by the live-fire test method, which verifies the effectiveness of the simulation calculation process and proves that the polycarbonate (PC) material is the most suitable substrate material for the silver paste printed circuit among the Polyimide (PI), Polycarbonate (PC), and Polyethylene terephthalate (PET) polymer materials which are the most common and cheapest one in market.

INDEX TERMS AUTODYN dynamic simulation, flexible film sensor, substrate film material.

I. INTRODUCTION

In the process of ammunition test and evaluation, the main parameters for the evaluation of the lethality caused by fragments to personnel on the battlefield after ammunition explosion are the speed and position when the fragments hit the target. A flexible circuit using silver paste printing technology can accurately acquire the speed and coordinates of ammunition fragments. The speed and coordinates measuring circuit are processed by printing the silver paste material onto the polymer substrate using 3D printing technology. The physical properties of the substrate film material, which will affect the velocity of the projectile and the degree of tearing of its holes also have a significant impact on the coordinates of the projectiles. Therefore, the selection of substrate film material will greatly affect the measurement accuracy of ammunition projectile velocity and coordinates.

The polymer substrate material has the characteristics of good transparency, flexibility and foldable, light weight, durability, and easy preparation. At present, there are three kinds of polymer films commonly used as the film substrate for silver paste circuits printing, all of them are: a) semi-crystalline thermoplastic polymers, which mainly are PET, Polyethylene naphthalate (PEN), and Polyetheretherketone (PEEK); b) Amorphous polymers, which mainly are PC, PES, and Polyetherimide (PEI); c) Amorphous polymers with high glass transition temperature, which mainly are PI, PAR, and PCO.

According to the classification of these three materials, PI, PC, and PET are chosen as the alternative polymer for

The associate editor coordinating the review of this manuscript and approving it for publication was Fabrizio Messina.

printed circuit substrate materials with rich raw materials and a relatively simple preparation process.

A polymer material chosen method that meets the requirements of projectile velocity and coordinate testing has been preliminarily determined through the combination of physical property experiments and AUTODYN simulation calculations. And the correctness of the substrate film selection method based on the combination of virtual and live has been verified through live-fire test.

II. THE PI, PC, AND PET MATERIALS SYNTHETIC, CHARACTERISTIC TEST, AND CHOSEN RESULTS

A. PI MATERIAL FILM

Polyimide is a kind of important special polymer material with excellent chemical stability, thermal stability, good mechanical properties, and insulation properties [1], [2]. Chosen the diamine monomer with semi-alicyclic structure(5(6)-amino-1-(4-aminophenyl)-1,3,3-trimethylindane/DAPI) reacted with aromatic dianhydride with different structures to synthesize PI particles with a half-alicyclic structure and prepare PI films; The relationship between molecular chain structure and mechanical properties will affect the strength and mechanical properties of the PI film.

This manuscript used PI material synthesized by a two-step thermal imidization method [3], [4]. And PI particle was synthesized with diamine monomer (DAPI) and different dianhydride (NTCDA, PMDA, 6FDA, BPADA) respectively. The synthesized PI material was recorded as 1-PI, 2-PI, 3-PI, and 4-PI respectively. The synthetic process is shown in Figure 1.

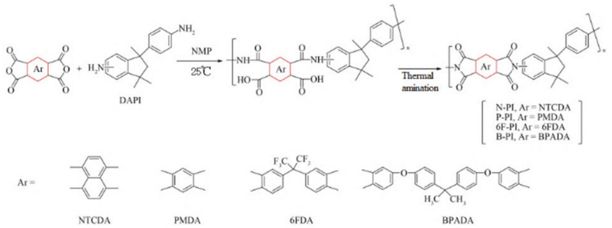


FIGURE 1. Tensile strength of the PI film.

Full dissolve the dried PI particles in chloroform, prepare a film casting solution that a solid content is 5%, filter it with a 0.45 μm Polytetrafluoroethylene (PTFE) filter, then stand still, defoaming, and pour it into a clean and smooth petri dish. The solvent slowly volatilizes at 25°C for 2 days to obtain solid films. Put the obtained film in a vacuum drying oven, and dry it at 120°C for 12 hours to obtain 4 kinds of PI films. The PI film characteristics are shown in Table 1.

The mechanical properties of the PI film are tested by AGS-X-10KN universal tensile tester according to ASTM D638 standard, and the tensile rate is 5mm/min. The test result is shown in Figure 2 and Table 2.

The mechanical properties of PI films synthetic by mixing different structures of aromatic dianhydride are significantly different. 1-PI and 2-PI films exhibit brittle fracture, while 3-PI and 4-PI films exhibit ductile fracture. The molecular chain of 1-PI material is relatively rigid, and the free volume of the molecular is relatively small, which hinders the activity of the molecular chain and cannot achieve high elastic deformation, making the film brittle fracture; The molecular chain of 2-PI material has greater rigidity, and the macromolecular chain arranging regularity is small, and its performance is also brittle fracture; The molecular chain of 3-PI film contains flexible ether bonds, the deformation of molecular chain is easy to occur, and the molecular weight of the polymer is highest, so the film shows a ductile fracture, and the film has the higher tensile strength and elongation at break; The 4-PI molecular chain is relatively rigid, and its free volume is quite large, resulting in relatively loose molecular combination and large movement clearance for molecular chain, which presents ductile fracture when the film is stretched. The elongation at break is about 72%. For ammunition projectile penetration, among those materials, the PI film with low tensile strength and elongation should be selected for silver paste circuit printing. In this article, 1-PI material is chosen for simulation calculation.

TABLE 1. Molecular weight and characteristics of PI film.

PI film	M_n g/mol	M_w g/mol	PDI
1-PI	31499	100633	3.19
2-PI	185908	270783	1.46
3-PI	231454	279317	1.21
4-PI	158451	275223	1.74

TABLE 2. Mechanical properties of the PI film.

PI film	σ_m /MPa	E_t /GPa	ε_b /%
1-PI	64.9±1.6	3.93	7.2±1.0
2-PI	82.7±1.8	2.46	5.9±0.9
3-PI	74.5±4.4	2.30	39.1±18
4-PI	68.3±3.1	1.33	73.6±6.3

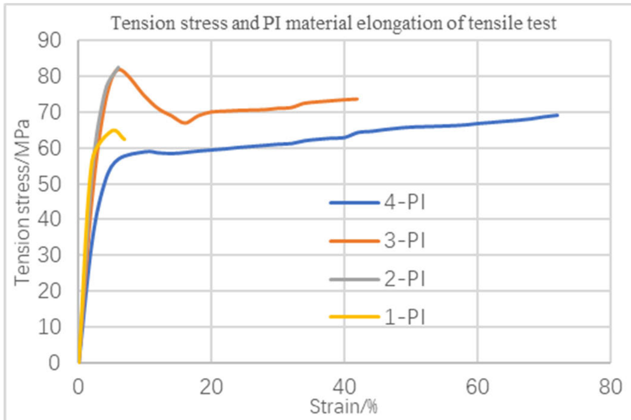


FIGURE 2. The synthetic process of PI.

B. PC MATERIAL FILM

PC is a kind of macromolecular compound in which a molecular chain contains a carbonate group. Its ester group is mainly aliphatic, aromatic, and aliphatic-aromatic. At present, the PC COTS products are BAPC. Its molecular structure is a linear macromolecule, and the molecular chain contains a large number of carbonyl and benzene rings, which makes the interaction between PC molecular chains large, and the entanglement is serious and difficult to disassemble, It is difficult to cause molecular sliding and deformation under outside force, so the PC material is stable, and have good transparency, high impact strength, excellent thermal stability, creep resistance, cold resistance, and electrical insulation. The chemical structure is shown in Figure 3.

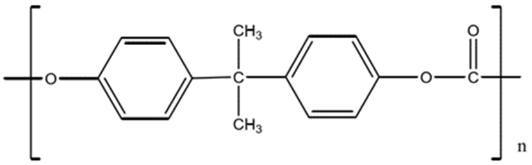


FIGURE 3. PC molecular structure.

In this article, PC films were synthesized using two kinds of PC particles by Bayer Company, which are PC3113 (MFR for 6g/10min) and PC2407 (MFR for 20g/10min). The synthesized PC films are called 1-PC and 2-PC respectively.

The synthesized process is to dry PC particles for 12h, and then sheet with a thickness of 300 and 400 μm respectively through the cast film extruder. The extrusion temperature of PC3113 is 280°C and 275°C for PC2407, and the casting roller temperature is 140°C. Use a biaxial tensile machine to conduct biaxial synchronous stretching of PC tape, the tensile temperature is 190°C, the preheating time is 120s, the tensile strain rate is 5%/min, and the longitudinal and transverse tensile magnification of the film is 2.5×2.5 and 3.0×3.0 respectively. The PI film's characteristics are shown in Table 3.

TABLE 3. Molecular weight and characteristics of PC film.

PC film	M_n g/mol	M_w g/mol	PDI
1-PC	15563	32600	1.92
2-PC	17594	41900	1.76

The mechanical properties of PC film are tested by AGS-X-10KN universal tensile tester according to ASTM D638 standard, and the tensile rate is 5mm/min. The test result is shown in Figure 4 and Table 4.

Compared with 2-PC film, the 1-PC film exhibits brittle fracture and the 2-PC film has better toughness. The molecular weight of the 1-PC film is small, and its molecular chain stiffness is large. According to the tensile test results, the elongation of the 2-PC film is greater than that of the 1-PC film, which indicates that its toughness is stronger than that of

TABLE 4. Mechanical properties of the PC film.

PC film	σ_m /MPa	E_t /GPa	ε_b /%
1-PC	47.9±1.6	2.46	12.3±1.0
2-PC	58.7±1.8	2.18	19.9±0.9

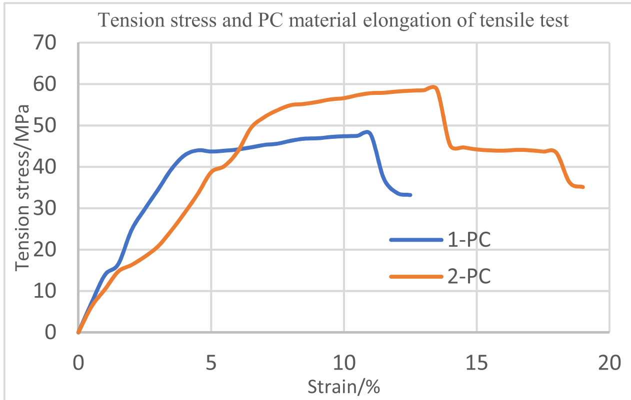


FIGURE 4. Tensile strength of the PC film.

the 1-PC film. When the projectile penetrates the film, it will consume more energy and speed. Therefore, 1-PI film with lower tensile strength and elongation at break is chosen for simulation calculation.

C. PET MATERIAL FILM

PET is a macromolecular material produced by Terephthalic acid (TPA) and Ethylene gratia (EG) through a polycondensation reaction. It is a linear macromolecular thermoplastic polymer with high crystallinity. PET has excellent mechanical properties, good electrical insulation, dimensional stability, creep, and fatigue resistance. The film prepared by PET has good mechanical properties, tensile and impact strength, and its strength and toughness are the best of all thermoplastic films. However, PET materials have fewer long-branched molecular chains and a low degree of entanglement between molecular chains. In addition, the current blow molding process has some problems such as low melt strength and poor material toughness, which will cause the film to become brittle and hard, and cannot generate a continuous film. Therefore, it is proposed to Blend modification of the PET materials to improve the molecular chain entanglement. Because polyethylene terephthalate-1,4-cyclohexane dimethyl ester (PETG) is an amorphous polymer and has good compatibility with PET, adding PETG can improve the mechanical properties of PET film. The PET and PETG materials mix ratio is shown in Table 5.

The synthesized method is to dry PET at 140°C for 6h, and PETG at 70°C for 6h, mix in different materials ratios, and then add it into the blow molding machine for blow molding. The temperature of each section of the extruder is 275°C, 282°C, 285°C, 285°C, 280°C, the outer temperature

TABLE 5. The material ratio of PET and PETG blends.

PET film	PET%	PETG%
1-PET	80	20
2-PET	60	40
3-PET	40	60
4-PET	20	80

is 270°C, and the screw speed of the extruder is 90r/min. The PET film's characteristics are shown in Table 6.

TABLE 6. Molecular weight and characteristics of PET film.

PET film	M_n g/mol	M_w g/mol	PDI
1-PET	14400	24800	1.72
2-PET	13200	23500	1.78
3-PET	14700	24700	1.68
4-PET	15100	27700	1.83

The mechanical properties of PET film are tested by AGS-X-10KN universal tensile tester according to ASTM D638 standard, and the tensile rate is 5mm/min. The test result is shown in Figure 5 and Table 7.

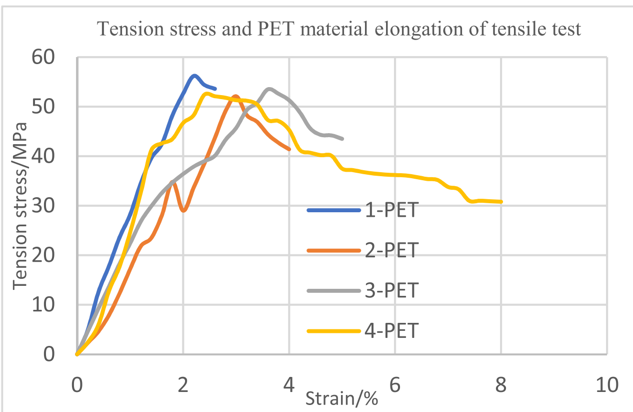


FIGURE 5. Tensile strength of PET film.

TABLE 7. Mechanical properties of PET film.

PET film	σ_m /MPa	E_t /GPa	ε_b /%
1-PET	56.2±2.3	2.97	2.6±0.02
2-PET	52.1±3.1	2.85	4.2±0.03
3-PET	53.5±3.4	2.77	5.1±0.03
4-PET	52.4±3.2	2.78	8.1±0.03

It can be seen from the test that with the increase of PETG mixed ratio, the tensile strength of PET film is gradually decreasing, but its elongation increases. The reason is that PETG material has good toughness, which effectively improves the toughness of the synthesized material after blending with PET, thus improving the elongation of the film. Therefore, the 1-PET film with a relatively small molecular weight and minimum elongation is chosen for simulation calculation.

III. AUTODYN-BASED SIMULATION OF THE PI, PC, PET FILM, AND CCL IN THE PROJECTILE PENETRATION PROCESS

Using the PI, PC, and PET film, the commonly printed circuits are generally printed by front and rear printing on a film substrate; thus, the features of substrate film characteristics will affect the velocity of projectiles after penetrating. Different types of substrate materials have different physical properties, thus different characteristics for response to high-velocity or low-velocity fragment penetration [5], [6]. They are different from each other in fragment deceleration. So, different testing results have been obtained, and selecting the most suitable substrate film material will minimize experimental errors.

Considering that the PI, PC, and PET film are macromolecular polymer materials when used as a flexible sensor substrate material to hinder the penetration of the projectile [7], [6], the physical properties of the material will have a significant deceleration effect on the projectile. The severity of the damage to the substrate material when the flexible film velocity testing sensor is broken (the size of the opening area of the substrate film material, the edge burr at the opening position) also has a certain corresponding relationship with the amount of kinetic energy carried by the projectile consumed [4]. For the flexible sensor using three common polymer films as substrate materials, to study the test accuracy of the velocity of the projectile [9], [10], it is necessary to determine the effect of the physical properties of the film material on the velocity of the projectile during the process of penetrating the film. The influence situation, the size of the projectile opening, and the burr on the edge of the hole at the opening position are simulated and analyzed, and the film that has the least impact on the projectile motion state is selected as the substrate material of the speed sensor.

ANSYS AUTODYN simulation software is currently the most common type of explicit dynamics analysis software. It focuses on the explicit solution, in addition to the implicit solution, and the main algorithm is the Lagrange algorithm. Meanwhile, it also uses the Euler algorithm and ALE algorithm. AUTODYN simulation software can be used to solve non-linear dynamic problems in the field of weaponry test evaluation, such as simulated high-velocity penetration and perforation of the projectile into a target, and is widely used in the field of national defense and trajectory simulation [11], [12], [13].

To simplify the simulation process, the ammunition fragments are specialized into spherical projectiles with a diameter of 7 mm. To study the velocity loss of projectiles with different velocity ranges after penetrating the flexible film substrate, the initial PI, PC, and PET thickness is 0.25mm, penetration velocity of the spherical projectile is set to 500m/s, 1000m/s, 1500m/s, 2000m/s, 2500m/s; The initial velocity is 1500m/s, the thickness of PI, PC, and PET film is set to 0.125mm, 0.15mm, 0.2mm, 0.4mm. The strain rate is determined by its mechanical properties, so the linear polynomial equation of state LINEAR_POLYNOMIAL can be used to describe its deformation response under the penetration of spherical projectiles [14], [15]. Considering that the three polymer materials have certain elastic and solid plastic properties, the material model MAT_ELASTIC_PLASTIC_HYDRO in AUTODYN can be used to simulate them.

The spheroidal projectile and the size of high polymer materials are adopted to build a finite element model, and the size of high polymer substrate film is set as 25cm×25cm×0.25mm. After mapped meshing, the Lagrange algorithm is adopted. The ERODING_SURFACE_TO_SURFACE contact is used for the contact between the spheroidal projectile and high polymer substrate film [16], [17], [18], [19]. The physical parameters of the spheroidal projectile and materials are shown in Table 8.

TABLE 8. AUTODYN simulation material parameters.

No.	Material	Density (g/cm3)	Elasticity modulus/GPa	Poisson ratio
1	Projectile	7.92	200	0.3
2	Printed circuit copper-clad laminate	8.9	108	0.34
3	PI	1.59	4.0	0.22
4	PC	1.22	2.5	0.39
5	PET	1.38	3.0	0.13

The hitting angle of projectiles on the battlefield is random. Considering the distance between the front and rear printed circuit can be controlled small enough in the velocity measurement process, the speed measurement error caused by the increased flying distance because of the projectile hit angle will also be small enough, and will not have a large impact on the velocity measurement results. Therefore, to facilitate the calculation in the simulation calculation, the hitting and penetrating direction of the projectile is given as the vertical circuit board. In the simulation calculation, the penetrated material was divided into a grid with a length of 0.05mm.

A. THE SAMPLE OF SIMULATION PROCESS FOR PENETRATING PI, PC, PET SUBSTRATE FILM, AND CCL PLANT

As example, the simulated process of 7 mm penetrating PI film at the velocity of 1500m/s is shown in Figure 6 and Figure 7 for the velocity loss in the penetration process.

When the projectile penetrates the PI polymer material, there is a large burr at the edge of the hole, but the edge of

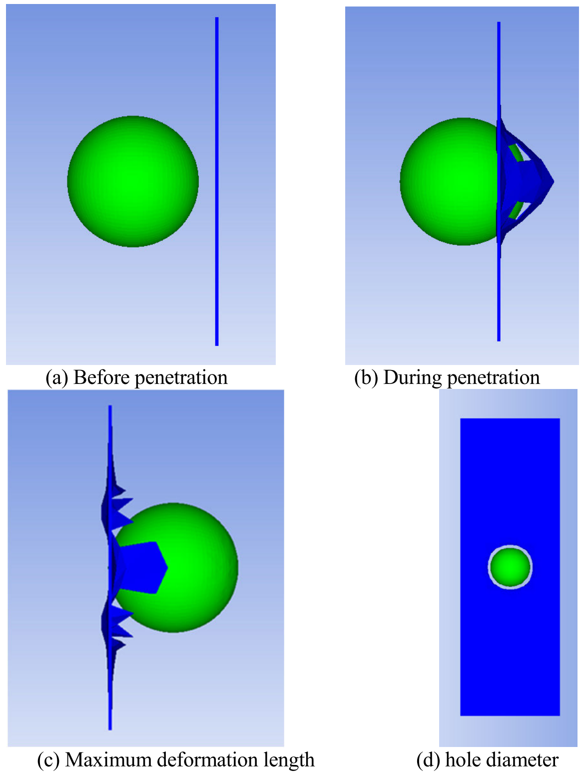


FIGURE 6. Process of 7mm spheroidal projectile penetrating 0.25mm-thick PI film.

the hole is relatively smooth, causing the PI polymer material to have a certain strength. During the penetration process, the projectile consumes more energy for tearing the substrate.

The simulated process of 7 mm penetrating PC film at the velocity of 1500m/s is shown in Figure 8 and Figure 9 for the velocity loss in the penetration process.

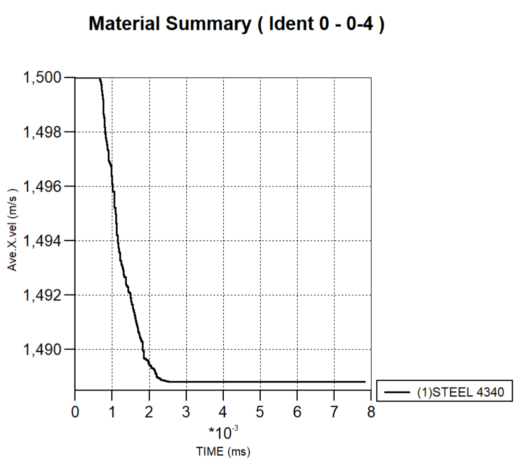


FIGURE 7. Velocity loss of projectile in the penetrating process.

When penetrating PC film, the burrs at the hole-breaking edge of the projectile are the largest among the three kinds of polymer materials, and the hole-breaking edge is the roughest among them, indicating that the high-speed

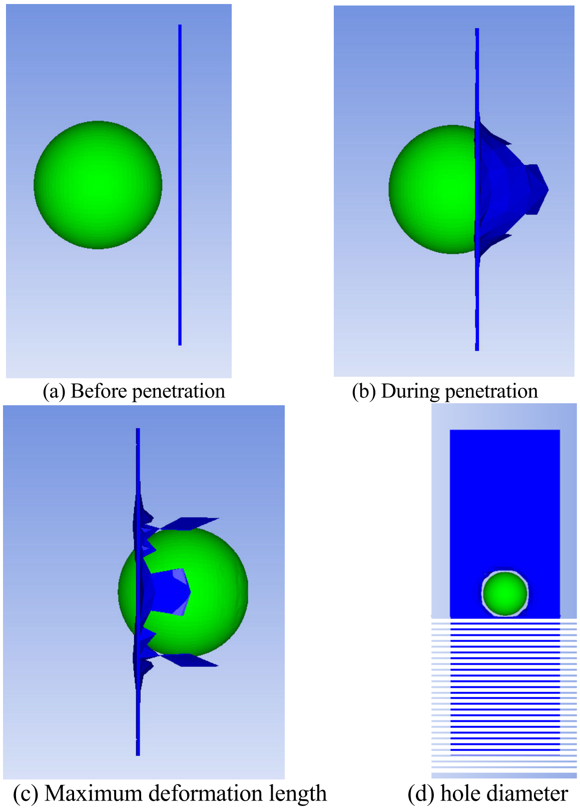


FIGURE 8. **Process of 7mm spheroidal projectile penetrating 0.25mm-thick PC film.**

projectile consumes more energy when penetrating PC polymer materials, and has a greater attenuation of speed.

The simulated process of 7 mm penetrating PET film at the velocity of 1500m/s is shown in Figure 10, and Figure 11 for the velocity loss in the penetration process.

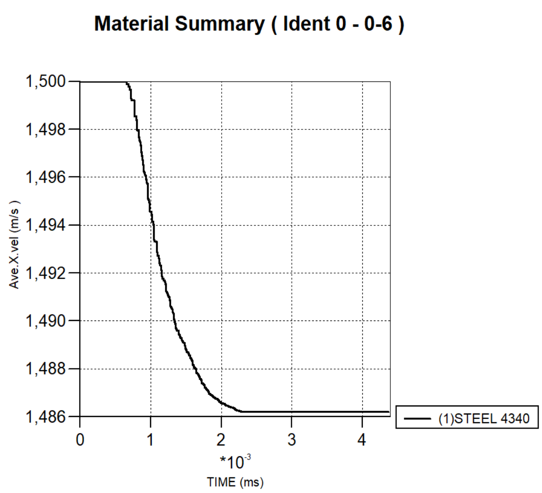


FIGURE 9. **Velocity loss of projectile in the penetrating process.**

When the projectile penetrates PEI film, the edge of the hole is relatively flat, and the edge burrs are less, which indicates that part of the energy is used to break the substrate

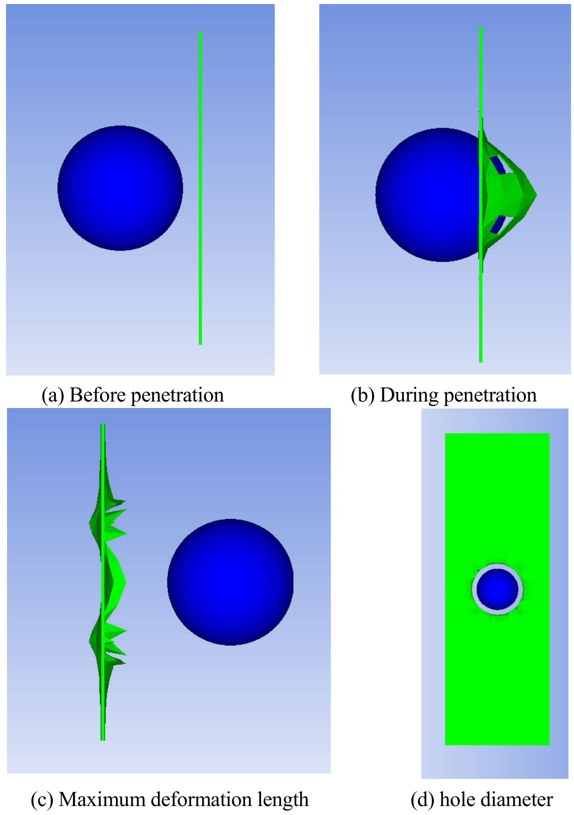


FIGURE 10. **Velocity loss of projectile in the penetrating process.**

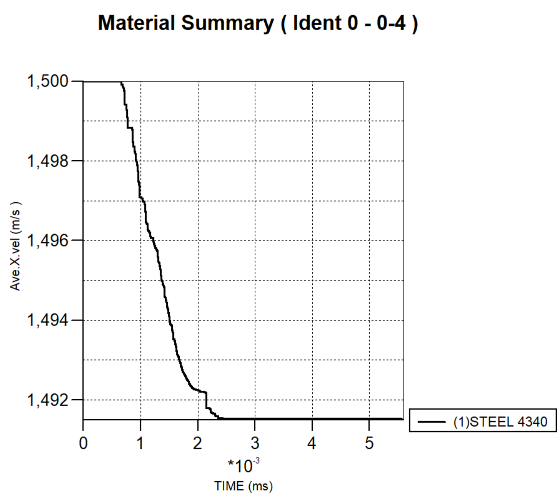


FIGURE 11. **Process of 7mm spheroidal projectile penetrating 0.25mm-thick PET film.**

material and give the substrate material fragments a certain flying speed during the penetration process.

The traditional velocity test target is a kind of comb target which is a circuit printed on a copper-clad plate C,B(CCLC,B#. The CCL is made of metal and has good electrical conductivity, but its thickness is larger than that of the flexible film and its hardness is higher. The speed of the material is greatly affected. As a comparison of the PI, PC, and PET film materials, the penetration simulation of the projectile on the CCL was carried out. See Figure 12 for the simulation process of a 7mm projectile penetrating 1mm CCL, and Figure 13 for the velocity loss of the projectile in the penetration process.

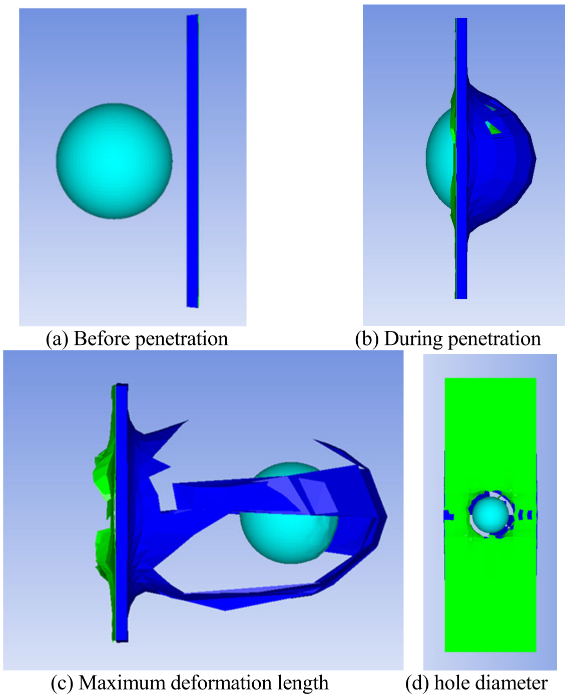


FIGURE 12. Velocity loss of projectile in the penetrating process.

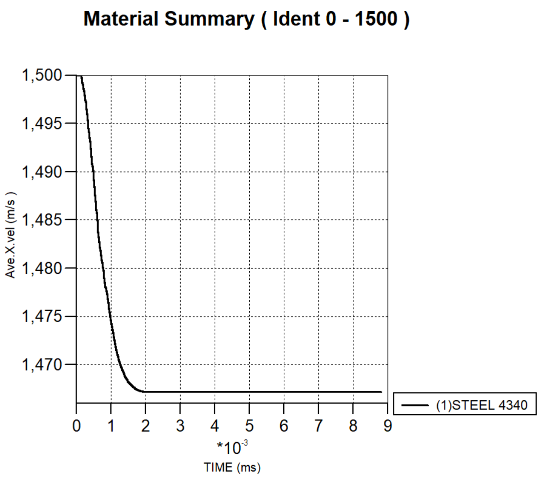


FIGURE 13. Process of 7mm spheroidal projectile penetrating 0.25mm-thick CCL.

When the projectile penetrates the CCL, the deformation of the edge of the hole is larger and the deformed copper plate is torn and stretched by the projectile, and the shape of the CCL perforation is irregular. This indicates that the high-speed projectile needs to consume a lot of energy to deform the copper plate when penetrating, so the attenuation of the speed will be far greater than that of the polymer material.

Due to the high strength and density of the CCL, to ensure speed measurement accuracy, it is necessary to reduce the thickness of the base copper plate when making the comb-shaped circuit as much as possible. However, the strength will be too thin enough to support the erection of the comb-shaped circuit, which affects its convenience of use. Therefore, it is necessary to optimize the design scheme of the CCL circuit or select a new substrate material.

B. DATA ANALYSIS OF THE PI, PC, PET, AND CCL PENETRATION PROCESS AT THE SAME THICKNESS BUT DIFFERENT PENETRATION VELOCITIES

By using AUTODYN software, a penetration model is built to study the maximum deformation length of film during penetration as well as the hole diameter and kinetic energy loss after penetration when the spheroidal projectiles with different velocities (500m/s, 1,000m/s, 1,500m/s, 2,000m/s, and 2,500m/s) penetrate the common substrate films (0.25mm-thick PET, PI, and PC films) used in silver paste printing and 1mm CCL target. The data obtained are shown in Table 9 to Table 12.

TABLE 9. Parameters of 7mm spheroidal projectile penetrating 0.25mm-thick PI film at different velocities.

PI film	500	1000	1500	2000	2500
Hole diameter	11	9	9.3	8.9	8.5
Max. deformation length	3.84	4.1	4.46	1.43	1.21
Velocity loss	1.9m/s	3.5m/s	5.5m/s	6.5m/s	7.8m/s

To compare the changes in the penetrating hole diameter of the three kinds of film substrate materials after being penetrated by the projectile, the diameter of the hole after the 7mm diameter projectile penetrated the PET, PI, PC film substrate materials, and the CCL at different speeds was drawn. The change curve is shown in Figure 14. It can be seen that the hole diameter of PC is the smallest under the impact of the low-speed projectile, and the hole diameter is also very stable under the impact of the medium-speed and high-speed projectile.

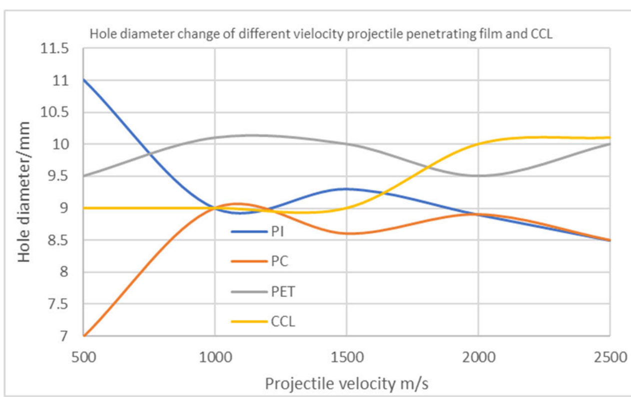


FIGURE 14. Change of hole diameter of different materials after penetration.

To compare the change of the maximum deformation length of the penetrating hole edge of the three kinds of film substrate materials after being penetrated by the projectile, the maximum deformation length of the 7mm diameter projectile after penetrating the PET, PI, PC film substrate and CCL at different speeds was drawn. The deformation length change curve is shown in Figure 15. PI, PC, and PET film's deformation lengths all change in a small size range.

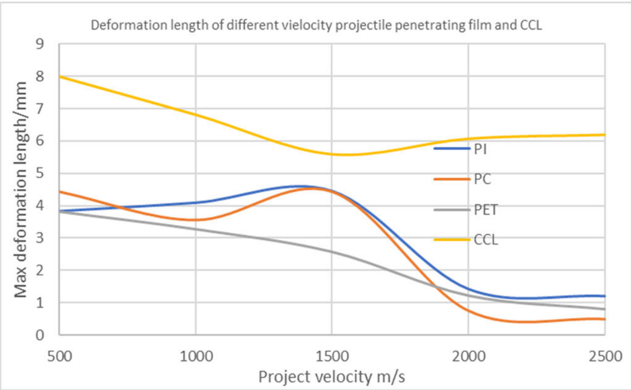


FIGURE 15. Change of maximum deformation length of different materials after penetration.

To compare the influence of the three kinds of film substrate materials on the velocity attenuation of the projectile after being penetrated by the projectile, the penetration velocity changes of 7mm diameter projectiles after penetrating PET, PI, PC substrate films, and CCL at different speeds are drawn. curve, as shown in Figure 16.

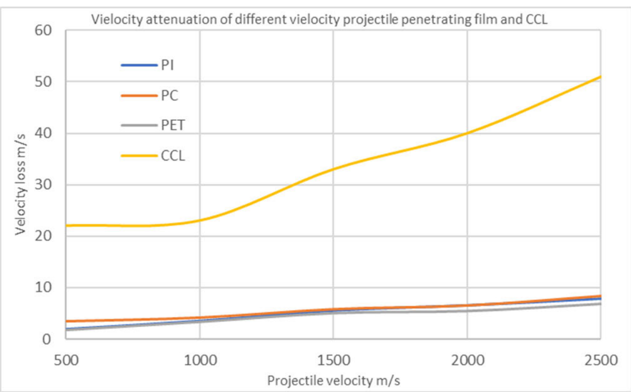


FIGURE 16. Change of velocity loss of projectile after penetrating through different materials.

Based on the analysis of analog simulation results, at medium velocities (1,000m/s-2,000m/s), PI, PC, and PET substrate films produce similar velocity loss on the projectile; at very high velocity (2,000m/s-2,500m/s) or very low velocity C,B(500m/s-1,000m/spenetration, PET film produces the minimum velocity loss.

At low and medium velocities (500m/s-1,500m/s), PET film has the smallest maximum deformation, while at high velocity (1,500m/s-2,500m/s) penetration, PC film has the smallest maximum deformation. At all velocities, PC film has the smallest hole diameter.

C. DATA ANALYSIS OF THE PI, PC, PET, AND CCL PENETRATION PROCESS AT THE SAME PENETRATION VELOCITY BUT DIFFERENT THICKNESSES

Similarly, for common substrate films used in silver paste printing (PI, PC, and PET films) under the condition of different thicknesses (0.1mm, 0.2mm, 0.4mm, and 0.6mm), AUTODYN software is used for the simulation of maximum deformation length of the film, hole diameter after projectile penetrates the film, and projectile velocity loss after spheroidal projectile penetrates the film, etc., in the case that 7mm spheroidal projectile penetrates the substrate film at 1,500m/s, and the data obtained are shown in Table 13 to Table 15.

TABLE 10. Parameters of 7mm spheroidal projectile penetrating 0.25mm-thick PC film at different velocities.

PC film	500	1000	1500	2000	2500
Hole diameter	7	9	8.6	8.9	8.5
Max. deformation length	4.42	3.55	4.42	0.76	0.5
Velocity loss	3.5m/s	4.2m/s	5.8m/s	6.5m/s	8.3m/s

TABLE 11. Parameters of 7mm spheroidal projectile penetrating 0.25mm-thick PET film at different velocities.

PET film	500	1000	1500	2000	2500
Hole diameter	9.5	10.1	10	9.5	10
Max. deformation length	3.81	3.27	2.57	1.22	0.8
Velocity loss	1.7m/s	3.3m/s	5m/s	5.4m/s	6.8m/s

TABLE 12. Parameters of 7mm spheroidal projectile penetrating 0.25mm-thick traditional comb-shaped-circuit target at different velocities.

CCL	500	1000	1500	2000	2500
Hole diameter	9	9	9	10	10.1
Max. deformation length	8	6.82	5.6	6.08	6.2
Velocity loss	22m/s	23m/s	33m/s	40m/s	51m/s

TABLE 13. Parameters of 7mm spheroidal projectile penetrating PI film with different thicknesses.

PI film	0.1mm	0.2mm	0.4mm	0.6mm
Hole diameter	8.9	9.43	10	9.8
Max deformation length	0.08	4.46	2.7	3.9
Velocity loss	0.25	5.5	9.3	13.8

TABLE 14. Parameters of 7mm spheroidal projectile penetrating PC film with different thicknesses.

PC film	0.1mm	0.2mm	0.4mm	0.6mm
Hole diameter	9	8.6	9	9
Max deformation length	0.09	4.42	4.41	4.2
Velocity loss	0.2	5.8	10.4	15

TABLE 15. Parameters of 7mm spheroidal projectile penetrating PET film with different thicknesses.

PET film	0.1mm	0.2mm	0.4mm	0.6mm
Hole diameter	9	10	9.8	11
Max deformation length	0.54	2.57	2.86	3.3
Velocity loss	2.4	5	8.3	12

As Figure 17 shows below, it's the changing curve of the hole diameter of PET, PI, and PC substrate film with different thicknesses after being penetrated by a 7mm projectile.

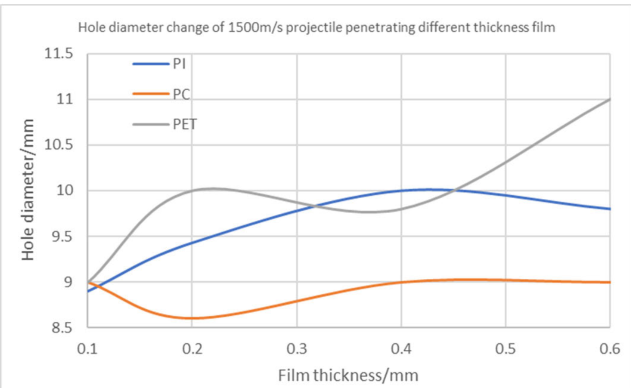


FIGURE 17. Relation between hole diameter and film thickness.

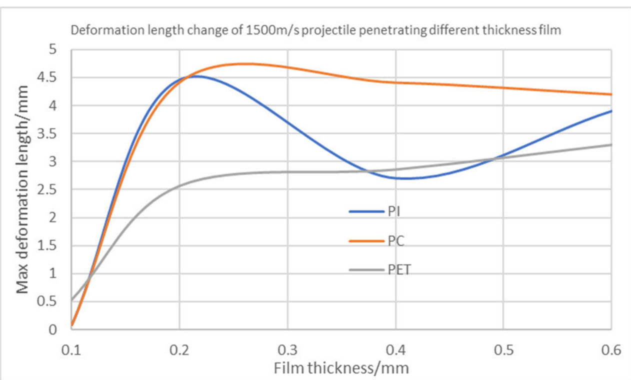


FIGURE 18. Relation between film deformation and film thickness.

As Figure 18 shows below, it's the changing curve of the maximum deformation length of PET, PI, and PC substrate film with different thicknesses after being penetrated by a 7mm projectile.

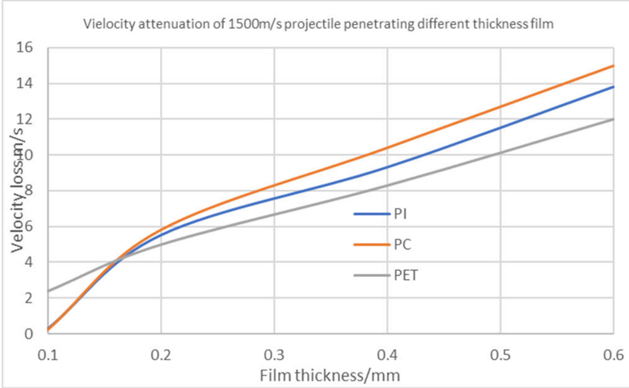


FIGURE 19. Relation between velocity loss and film thickness.

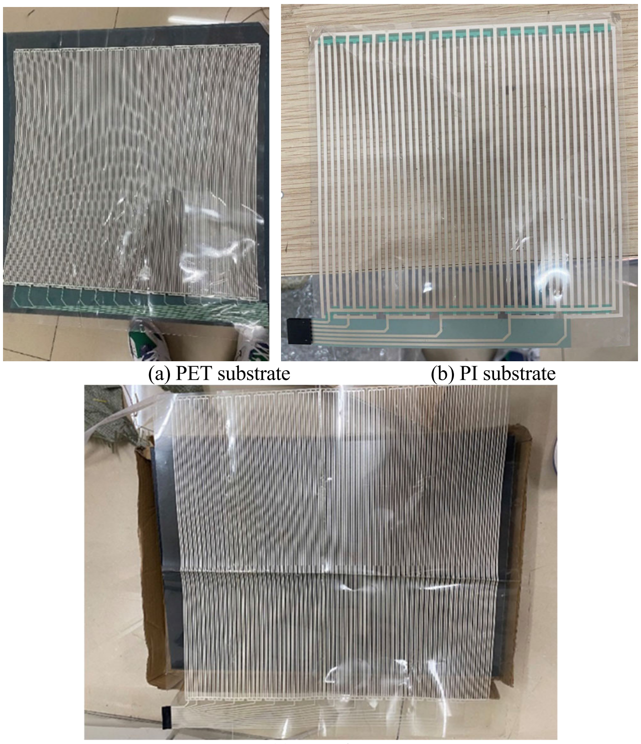
As Figure 19 shows below, it's the changing curve of velocity loss of 7mm projectile penetrating through PI, PC, and PET substrate film with different thicknesses.

It can be seen from the simulation results that the 7mm projectile penetrating PI, PC, and PET substrate films when the thickness of substrate film is between 0.1mm and 0.2mm, PC film produces the least velocity loss on the projectile, but when the thickness of substrate film is increased (from 0.4mm to 0.6mm), PET film produces the least velocity loss. Meanwhile, within the entire range of thickness, the hole diameter of PC film is the smallest after penetration.

IV. FABRICATION AND EXPERIMENTAL VERIFICATION OF FLEXIBLE FILM SUBSTRATE TESTING DEVICE BASED ON SIMULATION RESULTS

The film-printed circuit technology mainly uses high-precision spraying technology to spray and print the conductive medium on the film substrate according to the design plan. It is a high-precision metal material printing process. The conductive medium is printed on the flexible substrate through different printing processes, and then the flexible substrate is subjected to an annealing process to obtain a designated circuit. The flexible film speed measuring device based on the silver paste printed circuit technology of the thin film substrate can be used as a substitute for the comb-shaped speed measuring target of the copper-clad laminate. In the selection of the base film material, considering that the projectile used in the test is a small-diameter high-speed projectile, and at the same time using silver paste printing technology on the film surface to make a thin-film comb-shaped target, the base film needs a certain strength and thickness, according to the simulation calculation results. The transparent PI, PC, and PET film were used as the film substrate for the silver paste printed circuit to fabricate and test the flexible film sensor. In the design scheme of the flexible film sensor, the positive and negative lines are printed on one side of the film substrate, and the insulating layer is printed at the intersection of the positive and negative lines.

PI, PC, and PET films were selected as the substrate materials of the flexible film sensors, and silver paste printed circuits were fabricated for live-fire tests. In the case of ensuring the toughness of the flexible sensor system, a film with a thickness of 0.2 mm was selected as the electrode printing film. see figure. See Figure 20.



(a) PET substrate (b) PI substrate

(c) PC substrate

FIGURE 20. Fragment velocity measuring circuits of silver paste printed on PET, PI, and PC film.

The influence of the silver paste printed velocity measuring circuit with PI, PC, and PET films as the substrate material on the test results of the projectile velocity was tested and verified by the static explosion of ammunition live-fire test. Since the laser screen target has no solid target surface, it does not affect the change in the speed of the projectile. Therefore, the laser screen target is used as the reference object for the speed test to compare and test the influence of the substrate film on the speed of the projectile. The layout method of the test site is shown in Figure 21. A laser screen target is arranged at a distance of 12m, 16m, and 18m from the explosion point, after each live-fire test, the laser screen target and silver paste printed speed measuring circuit change their positions together. The silver paste printed speed measuring circuit with the PET, PI, and PC films as the substrate is arranged on one side of the laser screen target.

The silver paste printed speed measurement circuit with PET, PI, and PC films as the substrate consists of two flexible film target surfaces (start and stop flexible sensors) to form a speed measurement interval (target spacing is 181mm), start the flexible film sensor and stop the flexible film The distance between the thin film sensors is 181mm, and the speed of the fragments is calculated by measuring the time interval between the two thin film sensor tachometer circuits

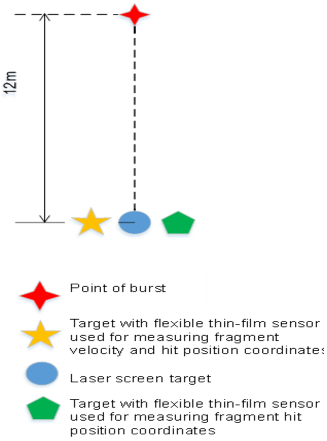


FIGURE 21. The arrangements of the targets in the test field.

(including the polycarbonate substrate film) by testing the fragments.

The trigger method adopts the disconnection trigger in the external trigger. The disconnection connects the test explosive device and the acquisition and storage device. After the explosion, the fragment penetrates the film line. At the moment of penetration, the flexible film sensor is activated to generate a fragment hit signal, and the flexible film sensor is stopped to generate projection. The object pierces the signal. The acquisition and storage device collects the signal and transmits it to the host computer software through the wireless network. The host computer displays the actual breakdown position and calculates the fragment breakdown position coordinates and speed. When the projectile passes through the laser light curtain target, the speed of the projectile is calculated directly from the front and rear target surfaces of the light curtain target.

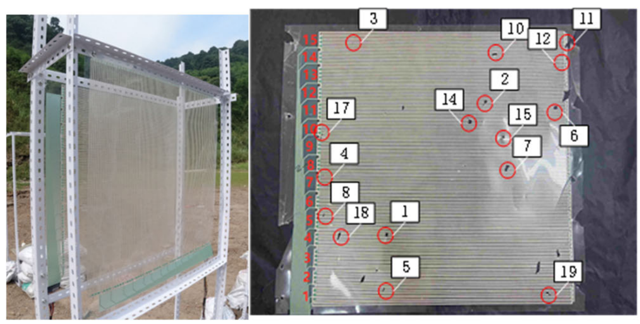


FIGURE 22. The layout of fragment velocity measuring circuits of silver paste printed on three kinds of films and the state after the test.

As Figure 22 shows, the irregular holes on the substrate film are caused by non-metallic materials (aggregates), excluded from test results. Table 16 to Table 18 is the velocity measurement results of fragment velocity measuring circuits of silver paste printed on PC, PI, and PET film and the velocity measurement results on the laser screen target.

From the test results of the projectile velocity test after the static explosion of the explosive, it can be seen that the silver paste-printed flexible film sensors with three

TABLE 16. Velocity sensor test results of PC film.

S/N	Position from the explosion center	Substrate film sensor (m/s)	Laser screen target (m/s)	Difference value (m/s)
1	12m	1847.03±12	1833.48±23	13.55
2	16m	1732.82±13	1710.21±25	13.61
3	18m	1626.01±12	1617.65±22	8.36
4	1500m/s projectile simulation results		5	

TABLE 17. Velocity sensor test results of PI film.

S/N	Position from the explosion center	Substrate film sensor (m/s)	Laser screen target (m/s)	Difference value (m/s)
1	12m	1879.32±17	1900.17±31	20.85
2	16m	1692.74±20	1715.37±34	22.63
3	18m	1602.35±18	1620.01±37	17.66
4	1500m/s projectile simulation results		5.5	

TABLE 18. Velocity sensor test results of PET film.

S/N	Position from the explosion center	Substrate film sensor (m/s)	Laser screen target (m/s)	Difference value (m/s)
1	12m	1882.54±16	1913.76±31	31.22
2	16m	1746.73±19	1769.59±33	27.86
3	18m	1652.84±23	1682.69±37	29.85
4	1500m/s projectile simulation results		5.8	

kinds of film materials as the substrate can be used as the velocity measurement target for the velocity test of the explosive projectile. The attenuation effects are different, and the degree of velocity attenuation is similar to the results of the dynamic simulation test using the AUTODYN software. When the PC film is used as the printed circuit substrate, the velocity attenuation effect on the fragments is the smallest. The speed test results are similar to the laser screen target speed measurement results.

The differences in the hole diameters on the silver paste printed flexible sensors based on the three film materials are small after being penetrated by the projectile, which is easily covered by the hole measurement error. It is difficult to verify through this static explosion test. The practical application of the flexible sensor projectile hit position coordinate test will be further verified.

V. CONCLUSION

Using the AUTO-DYN method to simulate the dynamic process of fragment penetrating the substrate membrane of the flexible film sensor, selecting the film material that has the least effect on the projectile velocity measurement under the condition of projectile penetration is the basis for researching the new type of ammunition fragment velocity testing equipment.

Through simulation calculation, it is found that on the condition of the thickness of the sensor substrate film is equal and thicker (> 0.2mm), the velocity attenuation of the three polymer films is similar at medium and low speed (<1500m/s), PET film's deformation is the smallest, and PC film's perforation is the smallest; At high speed (>1500m/s), PET film has the least velocity loss, and PC film has the least deformation and perforation.

In live-fire test, when the fragments hit the thin film (about or less than 0.2mm) with a regular ammunition projectile speed (about 1500m/s or above), the PC film has the smallest velocity loss, and the hole diameter and deformation of PC film are the smallest under all thickness conditions. Computational and experimental tests verify the scientific validity of PC material as the best sensor film substrate for ammunition endpoint efficacy testing equipment at the 0.2mm PC and PET film.

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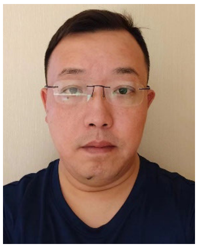

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