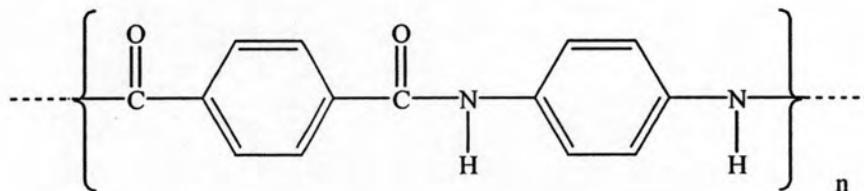# CHAPTER II

THEORY

2.1 Kevlar Aramid Fiber

Kevlar Aramid Fiber was commercialized by DuPont in 1972. Kevlar Fiber is poly (p-phenylene terephthalamide) (PPD-T) which is the one of para-orientated aromatic polyamides. The chemical structure of Kevlar is shown below.

The major types of Kevlar filament yarns at present include the followings:

- Kevlar	Tire yarn
- Kevlar29	All-purpose yarn
- Kevlar49	High modulus yarn
- Kevlar68	Moderate modulus yarn
- Kevlar100	Colored yarn
- Kevlar119	High elongation yarn
- Kevlar129	High tenacity yarn
- Kevlar149	Ultra-high modulus yarn

Table 2.1 Typical properties of Kevlar aramid yarns (Yang, 1993)

Yarn properties	Kevlar 29	Kevlar 49	Kevlar 68	Kevlar 119	Kevlar 129	Kevlar 149
Tensile strength,						
gpd	23.0	23.0	23.0	24.0	26.5	18.0
Kpsi	420	420	420	440	485	340
Initial modulus,						
Mpsi	10.3	17.4	14.4	8.0	14.0	21.0
Elongation, %	3.6	2.8	3.0	4.4	3.3	1.5
Density, g/cm^3	1.44	1.45	1.44	1.44	1.45	1.47
Moisture regain, % 25 °C , 65% RH	6	4.3	4.3	-	-	1.5

Yarn properties determined on 10 inch twisted yarns (ASTM D-885)

Kevlar aramid fiber is introduced to the high performance fiber because of its outstanding properties. It has higher breaking strength than steel wire, industrial nylon, and polyester yarns. It also has a much higher tensile modulus than fiberglass, nylon, and polyester fibers. Whereas, it possesses lower density than steel wire and glass fiber. These are the reasons why Kevlar-reinforced structures have light weight and high strength as well as stiffness. Kevlar fiber is stable at relatively high temperature. It has a very small shrinkage at elevated temperature, low creep, and relatively high glass transition temperature. It also has other excellent properties such as corrosion resistance, electrical insulation, and chemical resistance. These outstanding properties make Kevlar

fiber products useful for various applications particularly for the ballistic armor application (Yang, 1993).

The introduction of Kevlar aramid fiber in armor applications is extended because its superior mechanical properties which attribute to highly crystalline and highly oriented structure of the Kevlar. The high tensile strength and sufficient elongation of Kevlar fiber provide them high toughness and high work to break for the transverse deformation. Moreover, its high elastic modulus provides fast and effective spreading out kinetic energy from a projectile (Yang, 1993).

Table 2.2 Chemical and physical properties of Kevlar aramid fiber(Yang, 1993)

Properties	Value
High melt temperature	530°C
Zero strength temperature	640°C
High glass transition temperature	375°C
Low density vs. glass (2.55) and steel (7.86)	1.44
Thermal stability	Relatively high
Combustibility	Low
Conductivity	Nonconductive
Specific strength and modulus	High
Creep	Low
Environmental stability in sea water, oil, solvents	Good

2.2 Polycarbonate (PC)

Carbonate linkage is produced by the reaction between polyhydroxy compounds with carbonic acid derivative. Product of this reaction is called polycarbonate. Polycarbonate was first synthesized by Einhorn in 1898 by the reaction of dihydroxybenzene, hydroquinone, resorcinol, phosgene in pyridine solution. The chemical structure of polycarbonate is shown below.
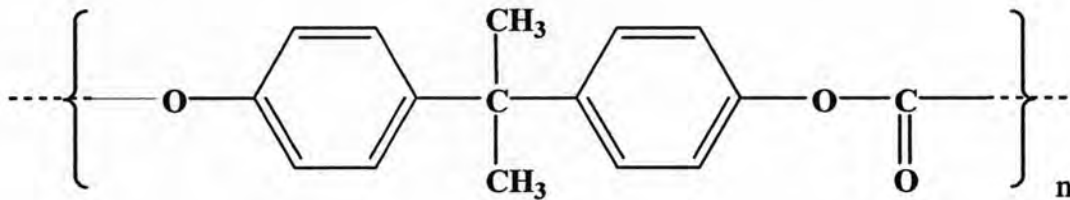
Polycarbonate is a strong, stiff, hard, tough, and transparent engineering thermoplastic. It can maintain rigidity up to 140°C and toughness down to -20°C or special grades even lower .Its advantages make polycarbonate to be one of the most widely use engineering plastics. Compact discs, riot shields, baby feeding bottles, electrical components, safety helmets and headlamp lenses are all typical applications for PC. Polycarbonate is usually formed via the reaction of Bis-phenol A with carbonyl chloride. At room temperature modulus and strength of polycarbonate are similarly to other glassy thermoplastics but toughness of polycarbonate is higher as shown in Table 2.4. Generally, amorphous thermoplastics are usually stiff and glassy below their glass transition temperature (T_g) and exhibit brittle fracture but polycarbonate does not obey this behavior (Daniels, 1989).

Table 2.3 Chemical and physical properties of polycarbonate (Daniels, 1989)

Properties	Value
Glass transition temperature	149°C
Melting temperature	250°C
Specific gravity	1.2
Tensile modulus	2.1-2.4 GPa
Tensile strength	56-67 MPa
Elongation at break	100-130 %
Impact strength	650-1000 J/m
Flexural modulus	2300-3200 MPa
Flexural strength	83 MPa
Water absorption	0.16% of volume
Chemical Stability	
Acid	good
Base	poor
Oil and Fat	excellent
Sunlight	good

Table 2.4 Physical properties of the most used reinforced thermosets and

Thermoplastics (Mark, 1996)

| Polymer type	T_g (°C)	Elastic modulus (GPa)	Tensile stress at break (MPa)	Elongation at break (%)	Impact strength (J/m)
Thermoplastics					
ABS	110	2.07	41.00	5.00	270.00
Nylon 6,6	57	2.76	78.78	60.00	40.00
Polycarbonate	150	2.34	65.08	110.00	850.00
Polyester (PBT)	30	1.93	56.17	50.00	40.00
Polyethylene (PE)	-125	0.2-0.7	27.00	100.00	133.00
Thermosets					
Epoxy resin	120-190	2.8-4.2	55.0-130.0	-	5.3-53.0
Polyimide	>280	3.2	55.80	-	-
Unsaturated polyester	100-170	2.0-4.4	40.0-90.0	<5.00	16.0-32.0
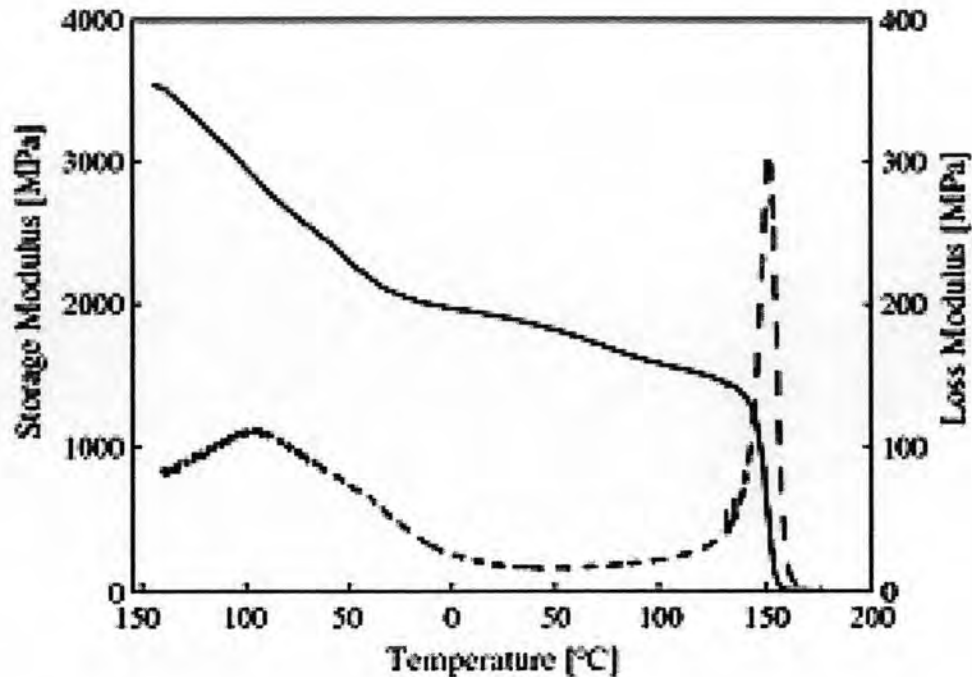
Figure 2.1 Storage and loss modulus versus temperature of
polycarbonate (Kroschwitz,1991)

Dynamic mechanical analysis introduces an explanation of molecular movement
of polycarbonate. The storage modulus (G') of Bis-phenyl A polycarbonate is slightly
temperature-dependent over wide range of temperature. As shown in Figure 2.1, the loss
modulus G'' passes though the maximum point approximately -100°C and 150°C which
are β relaxation and glass transition temperature (T_g) respectively. The high value of T_g
of polycarbonate compared with other thermoplastics is resulted from its bulky structure.
In addition, the unusual toughness of polycarbonate is suggested to be due to the broad
G'' peak in the low temperature range i.e. the β relaxation (Jacqueline, 1991).
Nevertheless, polycarbonate has some drawbacks such as high melt viscosity, notch
sensitivity. These disadvantages can be overcome by blending with other elastomers
which ABS is the most popular.

2.3 Acrylonitrile-Butadiene-Styrene (ABS)

ABS (acrylonitrile-butadiene-styrene) polymer is produced by the free-radical polymerization of styrene, acrylonitrile in the presence of polybutadiene. The polybutadiene is attacked by the radical and then grafted onto the styrene-acrylonitrile copolymer. The chemical structure of ABS is shown in the figure below.
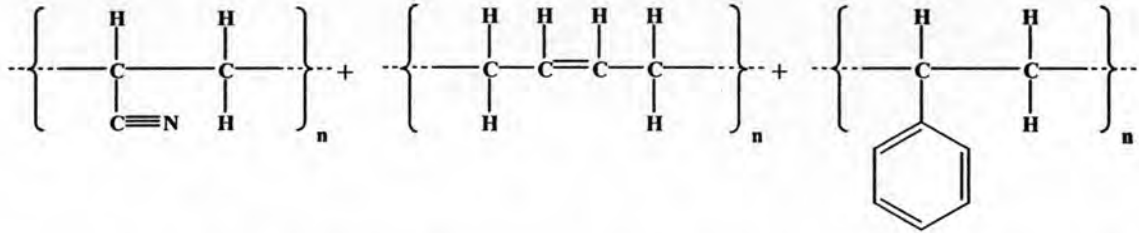
ABS polymer is between elastomeric and thermoplastic material. It exhibits good toughness and dimensional stability. The elastomeric component in ABS is a butadiene which is a discrete phase dispersed in thermoplastic component, polystyrene-co-acrylonitrile. ABS has effective impact energy dissipation mechanisms such as crazing and shear yielding, which inhibits crack formation. The actual properties of ABS depend on the ratio of each component in its structure. Furthermore, each component has its own advantage i.e. Acrylonitrile component gives chemical resistance and heat stability, butadiene provides toughness and impact strength whereas styrene gives rigidity and processability.

Table 2.5 Chemical and physical properties of ABS (Mark, 1996)

Properties	Value
Glass transition temperature	$100^{\circ}C$
Specific gravity	1.04-1.06
Tensile modulus	1900-2700 MPa
Tensile strength	32-45 MPa
Elongation at break	15-30 %

Impact strength	130-600 J/m
Flexural modulus	2700 MPa
Flexural strength	93 MPa
Water absorption	0.20-0.45% of volume
Chemical Stability	
Acid	excellent
Base	excellent
Oil and Fat	excellent

2.4 PC/ABS Blend

Polycarbonate (PC) and acrylonitrile-butadiene-styrene (ABS) blend is well known commercial products which have high thermal, mechanical, and impact performance. Positive and negative properties of PC and ABS are listed in Table 2.6.

Table 2.6 Positive and negative properties of PC and ABS

Behavior	PC properties	ABS properties
Positive	High heat distortion temp Mechanical resistance Low temperature toughness Transparency Dimensional stability Electrical properties	Economical Processability Impact strength Notch sensitivity
Negative	Chemical resistance Processibility Notch sensitivity Stress cracking	Low heat distortion temperature

Blending between ABS and PC not only minimizes the disadvantages of PC but also introduces the other useful properties, such as glossiness and low-temperature toughness. PC/ABS is a ternary blend system of ABS particles embedded in a PC matrix or vise versa. In addition, in the even finer microstructure of ABS, it consists of rubber particles in SAN matrix as shown in Figure 2.2 (Seelig, and Giessen, 2004).
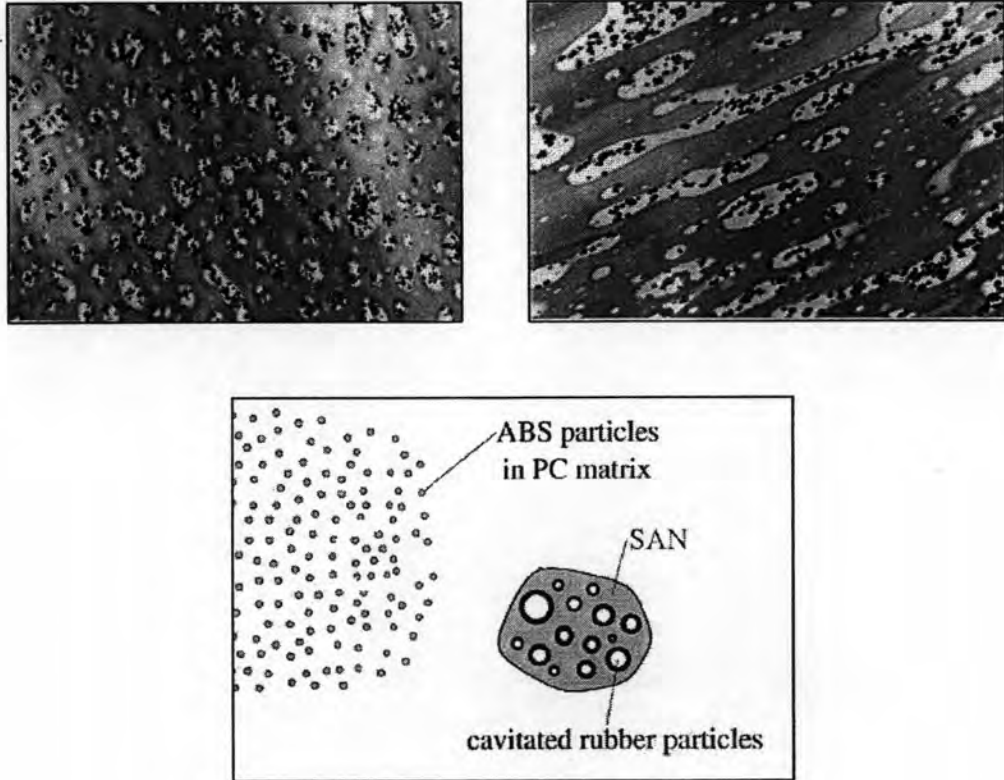

Figure 2.2 Microstructures of ABS particles in PC matrix (Seelig, and Giessen, 2004)

2.5 Toughening Mechanisms of PC/ABS Blend

Toughening mechanisms of PC/ABS blend depending on dispersion of rubber particle in a PC matrix include energy absorption by rubber particle, debonding at the rubber-matrix interface, matrix crazing, shear yielding or combination of shear yielding and crazing (Collyer, 1996).
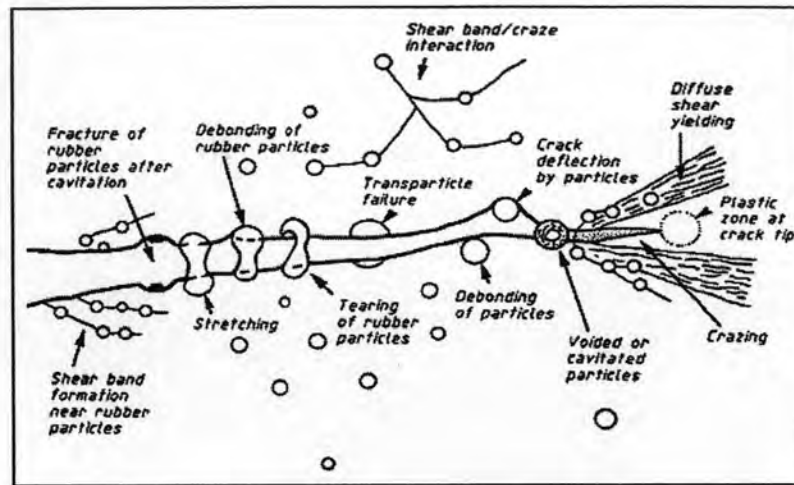
Figure 2.3 Toughening mechanisms in rubber filled modified polymers (Collyer, 1996)

2.5.1 Energy absorption by rubber particles

Merz et al. (1956) observed that the rubber particles in polymer matrix increased volume of stress whitening accompanied with elongation of material. This phenomenon is associated with the formation of many micro cracking. Merz suggested that during crack formation the fibrils of rubber particle will bridge across the fracture the surface and inhibit crack growth. The total fracture energy is the sum of energy to break the glassy matrix and to break the rubber particle.

2.5.2 Matrix crazing

Under tensile stress, crazing is initiated at the maximum strain point (maximum tri axial stress concentration) near the center of rubber particles. Craze growth is terminated by encountering with a neighbor craze. This mechanism can prevent craze growth and crack formation. The dense crazing influences high energy absorption because, when the craze appears, fibril network will from at the craze tip. This fibril network is high orientated, and contributed to high load bearing of craze. However, crack

can form by break down the craze fibril and forms void. This void expands slowly by rupture of surrounding craze fibril until void becomes crack.

2.5.3 Shear yielding

Shear yielding in the matrix phase plays a major role in the rubber toughening mechanisms. Shear bands are the barrier to propagations of craze, which delays material failure. Since molecular orientation in shear band is perpendicular to the crack growth direction, shear band is able to limit the craze growth.

In the case of rubber-toughened plastics, the rubber particles will dissipate the bulk strain energy by the cavitation, which leads to reduction in the yield stress of the materials. With this reason, shear yielding is easily formed and enhanced by the void in the matrix caused by the cavitated rubber particles (Collyer, 1996).

2.6 Advantages of Using Thermoplastics as Polymer Matrices in Composite Fabrication

Polymeric resins, thermoset and thermoplastic, are usually used as a matrix for Kevlar-reinforced composites. Thermoset composite is generally stiffer and higher thermal stability than thermoplastic composite. However, the thermoplastic composite possesses grater toughness, and impact resistance with relatively short processing time. The thermoplastic materials obtain their toughness from their long chain entangled molecules. The entanglement provides the matrix with strength and effective temporary crosslink. The molecules of thermoplastic have ability to slip pass one another when they get high stress enough because their chains are not fixed by a chemical bond. This is the reason why thermoplastics usually have higher toughness than thermosets. The thermoplastic resins including nylon, polyester, acrylonitrile-butadiene-styrene polymer, polyethylene, polypropylene, polycarbonate, and polystyrene are usually used in fiber reinforced composite fabrication (Cogswell, 1995).

In the present, although composite armor has been extensively developed by using various fibers, the matrix development for polymer and reinforced fiber compatibility is scarcely investigated because the restriction in lacking of tailor-made properties. This restriction makes armor composite can not achieve their highest efficiency which are their thickness, weight, and cost. The many papers expose the various properties of PC/ABS which can be fine tuned to achieve desired quality, such as toughness, modulus, viscosity, and polarity. Due to tailor-made properties of PC/ABS, it has high ability in development for high performance armor composite.

2.7 Usage of High Performance Fiber in Armor Applications

The introduction of high performance fiber in armor applications is extended because of their high strength and modulus. The strength of fiber is an important factor to defeat bullets. However, the strength alone cannot determine the performance of fiber to resist projectile. For example fiber glass and graphite fiber are strong (Table 2.7) but in the fabric form they cannot defeat a bullet or fragment as efficiently as Nylon or aramid. The important key parameters to stop projectile penetration of armor are ability to spread impact energy and capability to absorb tensile energy (Tyrone, 1991).

Table 2.7 Comparison of industrial filament yarns

Properties	Kevlar 29 aramid	DuPont nylon type 728	S-glass	E-glass	Type HT graphite
Tensile strength, MPa	2760	985	4580	3445	2760
Modulus, GPa	90	6	87	72	221
Elongation to break, %	4.0	18.3	5.4	4.8	1.25
Density, g/cm^3	1.44	1.14	2.64	2.57	2.75

Besides the mechanical strength of fibers, sonic velocity and specific energy absorption are very important parameters affecting in kinetic energy lost from projectile

at the impact point. The specific energy absorption evaluates capability to absorb energy locally and the sonic velocity evaluates capability to spread out energy. The fiber with high wave velocity will have greater volume of the fiber interacting with the projectile (Jacqueline, 1991). From these two parameters, it infers that the fiber which is appropriate in armor application should have high sonic velocity and specific energy absorption. Relationship between sonic velocity and specific energy absorption with the basic mechanical properties of material are shown in Eq. 2.1 and 2.2.

The velocity of wave propagation increases with the square root of fiber modulus and decrease with the square root of fiber density as displayed in Eq. 2.1 (Tyrone, 1991).

$$V_s = \sqrt{E/\rho} \qquad (2.1)$$

when
$$E = \text{modulus}$$
$$V_s = \text{sonic velocity}$$
$$\rho = \text{density}$$

Specific energy absorption depends on rupture stress and rupture strain as shown in Eq. 2.2.

$$E_{sp} = \frac{0.5\sigma_{rupt} \times \varepsilon_{rupt}}{\rho} \qquad (2.2)$$

when
$$E_{sp} = \text{specific energy absorption capability}$$
$$\sigma_{rupt} = \text{breaking strength}$$
$$\varepsilon_{rupt} = \text{strain of rupture}$$
$$\rho = \text{density}$$

The performance of major ballistic fibers is shown in Figure 2.4. In this figure, the sonic velocities of the fibers are plotted against their specific energy absorptions (Jacob, 2001).
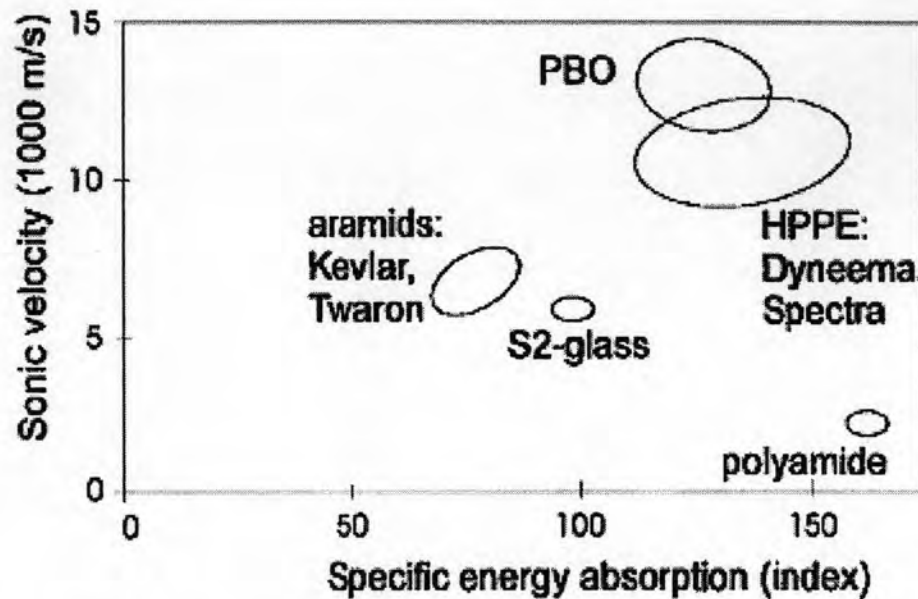

Figure 2.4 Sonic velocity and specific energy absorption of various fibers (Jacob, 2001)

2.8 Theories on Ballistic Impact

One of the most important types of armor consists of two parts which are the hard and rigid part and tough and flexible part. The hard and rigid part has ability to reduce the mass of the projectile by disintegration into small fragments. Furthermore, this part also decreases the impact velocity of the projectile, which the energy of the projectile will be easily absorbed by the flexible part which supports behind this hard layer. The tough and flexible part is made of ductile material. Its main function is to absorb the residual impact energy of fragmented parts of the projectile, which results in plastic deformation of the ductile material.
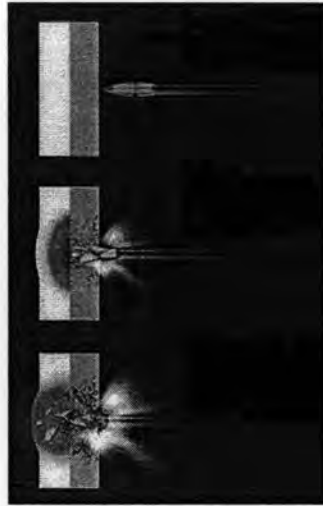
Figure 2.5 Schematic representation of principle of armor

Although various polymer matrices have high mechanical properties, they still cannot defeat a high velocity impact force from the projectile. In addition, the materials having high modulus and stiffness are usually brittle and fragile (crack notch sensitive). In the other hand, softer and tougher materials such as elastomers have an ability to dissipate impact force but cannot resist the penetration of the projectile at high impact velocity.

The introduction of polymer blending technique can relieve the shortcomings of the materials because properties of polymer blends, both thermosets and thermoplastics, can be fine-tuned for optimum stiffness and toughness simultaneously using appropriate blend pairs.

Fiber-reinforced composite materials have rapidly become an important class of ballistic resistant materials due to their outstanding mechanical properties, flexibility in design capabilities, and ease of fabrication. Additional advantages include high strength-to-weight and stiffness-to-weight ratios, and excellent impact resistance. Due to the light weight of fiber-reinforced plastic materials, they are being used increasingly by the military as armor. The composite material can be defined as a macroscopic combination of two or more distinct materials containing a reinforcing material (fibers or particles)

and a binder (matrix) material. Generally, when the composite encounters with a high-speed projectile, the reinforcing fiber in the composite will be stretched and transmitted impact energy along its length. The energy will transmit from the fiber which directly hit by projectile to other fiber at their crossover points. The simplest form of the impact can be explained by the impact of a projectile on a single fiber or yarn as shown in Figure 2.6 (Bryan, 2003).
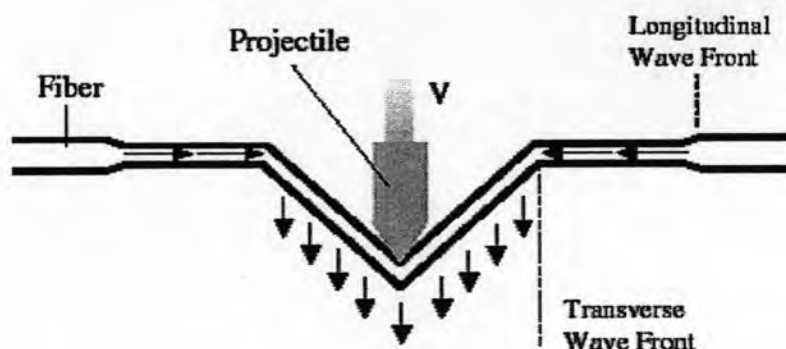

Figure 2.6 Projectile impact on a single fiber (Bryan, 2003)

The impact of a projectile on a composite normally generates two directions of response in a reinforcing fiber. There are longitudinal direction and transverse direction. When the impact of the projectile is applied, a longitudinal wave will propagates outward perpendicular to an impact point with a sonic velocity. In addition, a transverse wave will simultaneously propagate away from impact point. The reinforcing fiber behind transverse wave front is flowed toward an impact point in the direction of the projectile impact. The fiber deflection occurs until strain at the impact point reaches to breaking strain.

The important phenomenon happens simultaneously with the wave propagation is load sharing between primary yarns, the yarns are directly hit by the projectile, and secondary yarns, the yarns are transferred energy from yarns at the impact point, through cross over interaction. This phenomenon leads to unloading of the primary yarns. From a

study of Jacqueline in 1991, his experimental evidence suggested that up to 40-50% of total ballistic energy is absorbed by the secondary yarns. This result implies that a tightly woven of a fabric will be the most efficient. Therefore, the impact energy of a projectile can be absorbed through the other fracture mechanisms in armor composite.

2.9 Energy Absorption Mechanisms of Composite Armor

For the complete understanding of ballistic impact of composites, different damage and energy absorption mechanisms should be understood. The possible energy absorption mechanisms of a composite are deformation of primary and secondary yarns, delamination, and matrix deformation as shown in Figure 2.7. For the different composite systems, the different mechanisms can be dominant. In addition, properties of polymer matrix and reinforced fiber also affect to the energy absorption mechanisms of the composite.
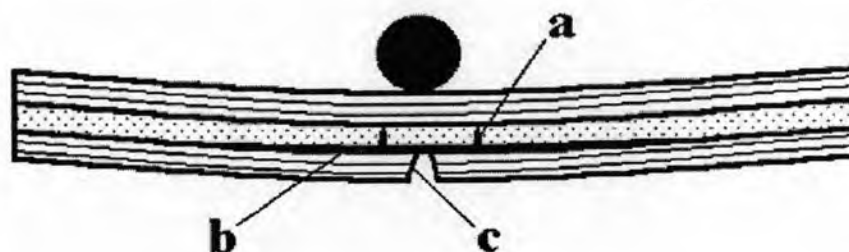

Figure 2.7 Three principal damage mechanisms for low velocity impact

a) matrix deformation, b) delamination, c) fiber failure

(Ellis, 1996)

Another damage mechanism of composites found in high velocity impact is shear plug. This phenomenon is due to the high stresses created at the point of impact. It shears and pushes forward a material around the projectile, which causing a hole slightly larger than the diameter of the projectile as shown in Figure 2.8.
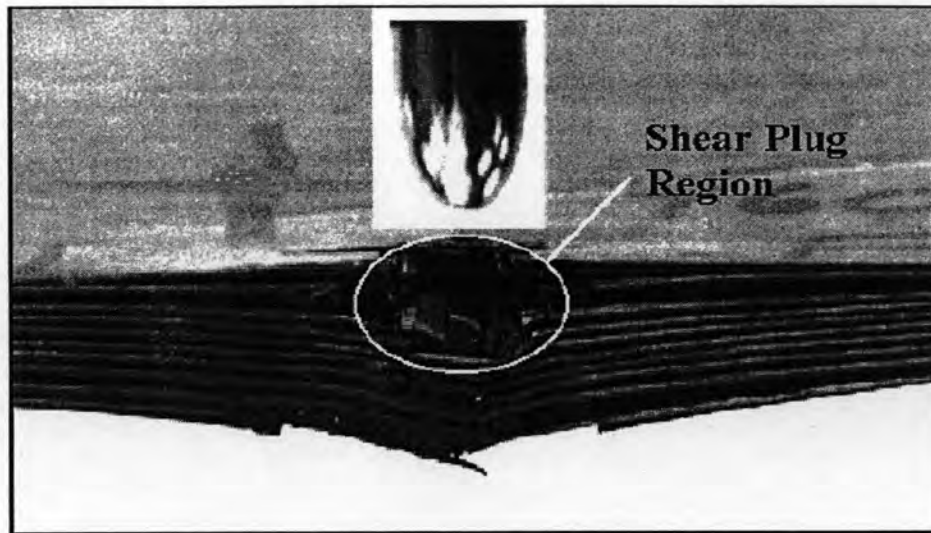
Figure 2.8 Photo of a projectile and specimen impacted near its V_{50} ballistic limit pointing out shear plug region (Ellis, 1996)

In composite fabrication, the addition of matrix resin to a woven fabric provides the composite to be strong enough to serve in normal applications. Whereas, the longitudinal wave velocity of the composite with a resin matrix is slowed by its rigid crossovers points. At these points, the longitudinal wave velocity will be extensively reflected, which results in a high strain gradient in the reinforced fiber and restricts transverse deflections of the composite. However, the bonded layers permit load transfer to secondary yarns through the continuum of a matrix and allow impact energy propagates in the thickness direction and spreads over a large area on back layers of the composite. This is an important mechanism for an armor design to stop very high velocity projectile. In order to minimize the effect of the rigid crossover points, which inhibits longitudinal wave propagation, some delamination between fiber and resin should be achieved. Moreover, some flexibility in transverse deflection of the composite is also necessary to get the maximum efficiency in armor applications.

2.10 Ballistic Standard (National Institute of Justice [NIJ]) for Body Armor Classification

Personal body armors covered by this standard are classified into seven classes, or types, by level of ballistic performance. As of the year 2000, ballistic resistant body armor suitable for full time wear throughout an entire shift of duty is available in classification Types I, IIA, II, and IIIA, which provide increasing levels of protection from handgun threats. Type I body armor, which was first issued during the NIJ demonstration project in 1975, is the minimum level of protection that any officer should have. Officers seeking protection from lower velocity 9 mm and 40 S&W ammunition typically wear Type IIA body armor. For protection against high velocity 357 Magnum and higher velocity 9 mm ammunition, officers traditionally select Type II body armor. Type IIIA body armor provides the highest level of protection available in concealable body armor and provides protection from high velocity 9 mm and 44 Magnum ammunition.

Type IIIA armor is suitable for routine wear in many situations; however, departments located in hot, humid climates may need to carefully evaluate their use of Type IIIA body armor for their officers. Types III and IV armor, which protect against high powered rifle rounds, are clearly intended for use only in tactical situations when the threat warrants such protection.

2.10.1 Type I

This armor protects against .22 caliber Long Rifle Lead Round Nose (LR LRN) bullets, with nominal masses of 2.6 g (40 gr) impacting at a minimum velocity of 320 m/s (1050 ft/s) or less, and 380 ACP Full Metal Jacketed Round Nose (FMJ RN) bullets, with nominal masses of 6.2 g (95 gr) impacting at a minimum velocity of 312 m/s (1025 ft/s).

2.10.2 Type IIA

This armor protects against 9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets, with nominal masses of 8.0 g (124 gr) impacting at a minimum velocity of 332 m/s (1090 ft/s) or less, and 40 S&W caliber Full Metal Jacketed (FMJ) bullets, with nominal masses of 11.7 g (180 gr) impacting at a minimum velocity of 312 m/s (1025 ft/s). It also provides protection against the threats mentioned in section 2.10.1.

2.10.3 Type II

This armor protects against 9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets, with nominal masses of 8.0 g (124 gr) impacting at a minimum velocity of 358 m/s (1175 ft/s) or less, and 357 Magnum Jacketed Soft Point (JSP) bullets, with nominal masses of 10.2 g (158 gr) impacting at a minimum velocity of 427 m/s (1400 ft/s). It also provides protection against the threats mentioned in sections 2.10.1 and 2.10.2.

2.10.4 Type IIIA

This armor protects against 9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets, with nominal masses of 8.0 g (124 gr) impacting at a minimum velocity of 427 m/s (1400 ft/s) or less, and 44 Magnum Semi Jacketed Hollow Point (SJHP) bullets, with nominal masses of 15.6 g (240 gr) impacting at a minimum velocity of 427 m/s (1400 ft/s). It also provides protection against most handgun threats, as well as the threats mentioned in sections 2.10.1, 2.10.2, and 2.10.3.

2.10.5 Type III

This armor protects against 7.62 mm Full Metal Jacketed (FMJ) bullets (U.S. Military designation M80), with nominal masses of 9.6 g (148 gr) impacting at a minimum velocity of 838 m/s (2750 ft/s). It also provides protection against the threats mentioned in sections 2.10.1, 2.10.2, 2.10.3, and 2.10.4.

2.10.6 Type IV

This armor protects against .30 caliber armor piercing (AP) bullets (U.S. Military designation M2 AP), with nominal masses of 10.8 g (166 gr) impacting at a minimum velocity of 869 m/s (2850 ft/s). It also provides at least single hit protection against the threats mentioned in sections 2.10.1, 2.10.2, 2.10.3, 2.10.4, and 2.10.5.

2.10.7 Special type

A purchaser having a special requirement for a level of protection other than one of the above standard types and threat levels should specify the exact test round(s) and minimum reference impact velocities to be used, and indicate that this standard shall govern in all other aspects.

2.11 Ballistic Penetration and Back Face Signature Criteria

Each part of one complete body armor sample shall be tested for resistance to ballistic penetration. The body armor has to completely resist to the ballistic penetration and depth of after fired backing material must not greater than 44 mm (1.73 in).

2.12 Test Method

Select the required test bullet for the armor type as specified in sections 2.10.1-2.10.7. Beginning with threat round number one, fire a minimum of three pretest rounds to ensure that the first test round fried will strike the target as aimed, using a suitable targeting device. These pretest rounds will also serve to "warm" or stabilize the temperature of the barrel before further testing. Set up the test equipment as shown in Figure 2.9. The backing material fixture will be rigidity held by a suitable test stand, which shall permit the entire armor and backing material assembly to be shift vertically and horizontally such that entire assembly can be targeted by the test barrel.
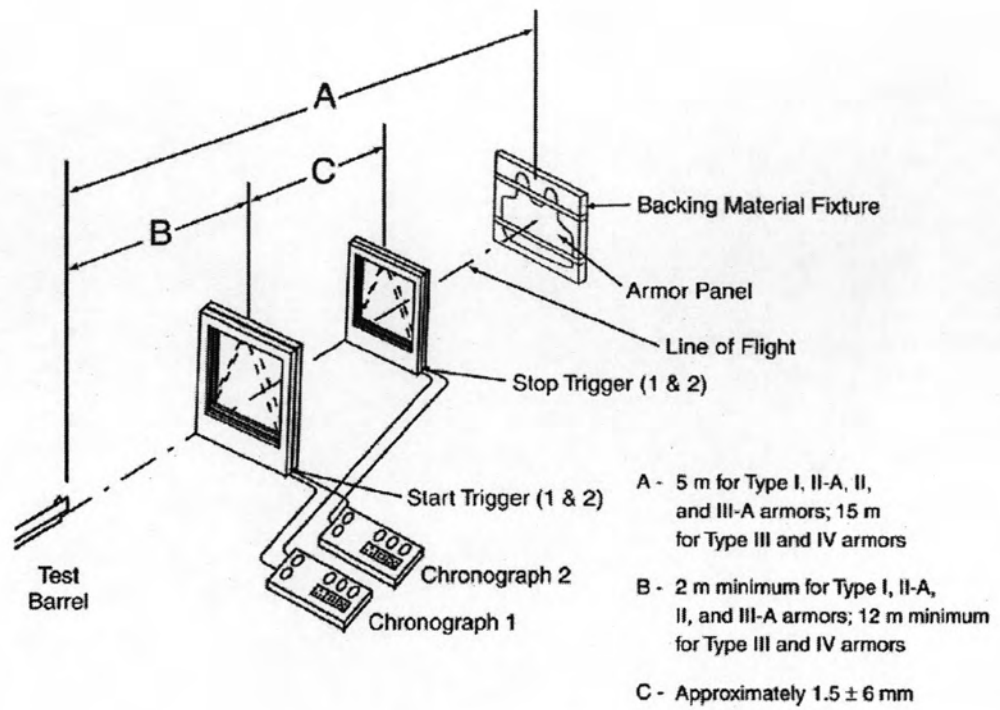
Figure 2.9 Test range configuration (National Institute of Justice [NIJ], 1997)