Transparent Armour Systems and General Applications

Gözde Sultan ALTUĞ[a,c], Tadao Deniz ÖZİSTEK[a], Savaş DİLİBAL[a,b], Sunullah ÖZBEK[a,c]

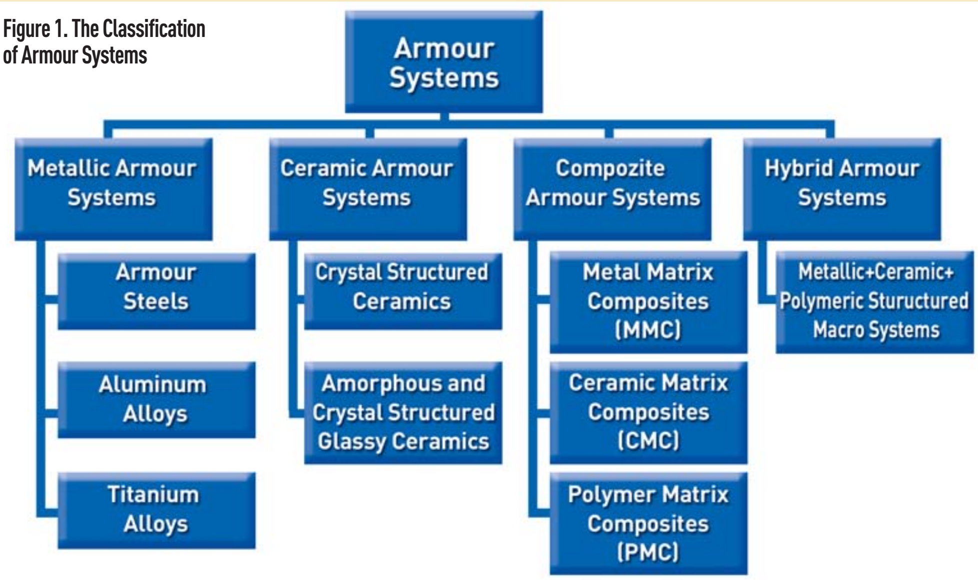
a Gedik University, Graduate School of Physical Sciences, Department of Defense Technologies, 34876, Kartal, İstanbul
b Gedik University, Faculty of Engineering, Department of Mechatronics, 34876, Kartal, İstanbul
c Gedik University, Faculty of Engineering, Department of Metallurgical and Materials Engineering, 34876, Kartal, İstanbul

1. Introduction

Human beings' basic drive to protect themselves and their shelters against various attacks throughout history has inevitably sparked the rapid advancements in armour systems and ballistics. In parallel with the recent technological developments, designing and producing more effective armour systems have gained considerable importance due the use of physically and mechanically highly enduring materials both in civil and military applications. Thanks to the use of advance production and heat treatment techniques in materials science and development of structure / features parameters, armours systems having higher toughness and hardness levels than metallic, ceramic, polymer and composite materials have been used in defence industry more effectively. The classification of currently used armour systems is displayed in Figure 1 below schematically.

Ballistics is a field of science dealing with the motions of projectiles such as bullets and missiles starting from the barrel as well

Figure 1. The Classification of Armour Systems



as their deformation behaviours when they hit the target. It is commonly classified into three main categories; internal, external and terminal ballistics. Internal ballistics examines the movements of bullet inside the barrel while external ballistics is about its movements during the flight under external effects. Terminal ballistics studies the effects of bullet on the target upon hitting. Armour systems are indispensable systems developed to protect vehicles and personnel against external threats such as bullets rocket etc. and shrapnel pieces with various sizes and speed levels in civil and military environments. The characteristics of armour systems and examination of deformation behaviours are directly related to terminal ballistics.

Recent military operations have clearly proven the vital importance of transparent armour systems which provide both personnel safety and visibility. Transparent armour systems are made of transparent materials which provide ballistics protection and optical transmittance and are integrated into whole system appropriately [1]. Today, these systems have a wide range of applications in both civil and military environments such as personal protection tools, face shields, riot shields, land, sea and air vehicles, building protection systems and explosive ordnance disposal practices [2]. In this respect, what is expected from transparent armour systems are as follows: effective single and multiple impact; resistance against explosions and scratches; low diffraction surface for a clear vision; low density for portability and long range; low panel thickness for a more efficient internal volume use; night vision; and high performance/cost ratio [3].

In order to meet above mentioned expectations, transparent armour systems are designed as a three-layered system; (a) hard layer aiming to deaden a bullet or break it into pieces by corroding; (b) energy absorbing intermediate layer that prevents thermal expansion and crack propagation; (c) back support layer surrounding fractured armour remains. Depending on the design, it is possible to place some extra intermediate layers to ensure the layers to stick well and reduce thermal expansion to minimum levels [1] (Figure 2).

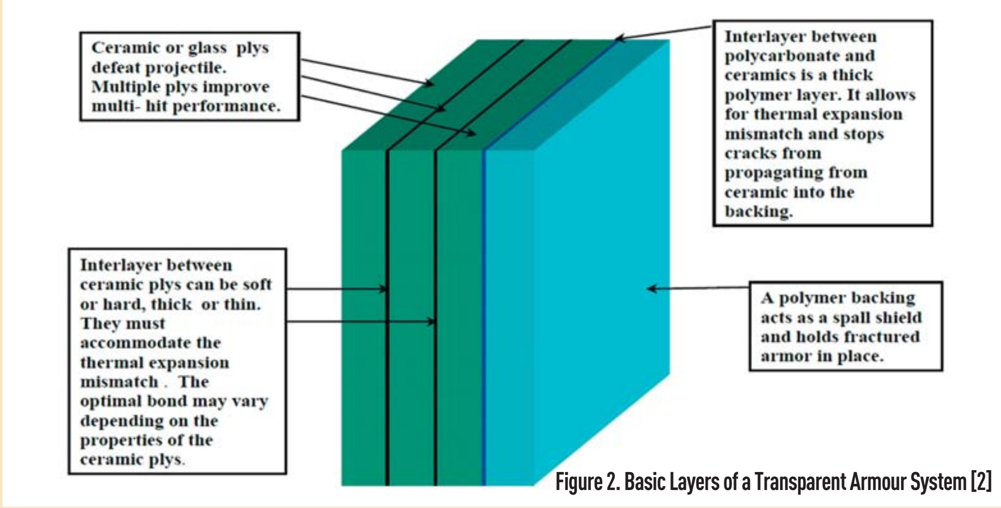


Figure 2. Basic Layers of a Transparent Armour System [2]

The materials preferred in transparent armour systems are glass, glass ceramic, single / polycrystalline ceramics, polymer and hybrid systems. Within the scope of this study, transparent armour systems will be examined under three main categories as displayed in Figure 3; ceramic, polymeric and hybrid armour systems.

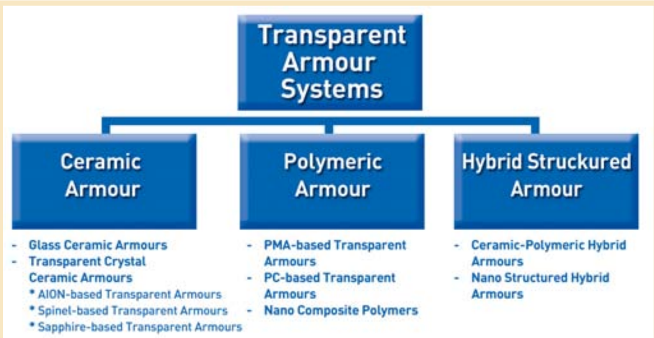


Figure 3. Classification of Transparent Armour Systems

2. Ceramic Armour Systems

2.1. Glass Ceramic Transparent Armours

Various types of glass such as normal glass, borosilicate glass and molten silica can be used as transparent armours. The ballistic resistance of these glass types can be increased by applying chemical or thermal processing. In addition, transparent glass-ceramic can be manufactured through controlled-crystallization of certain glass systems. In basic terms, glass and glass ceramic have certain advantages over other ceramic materials such as low cost, possibility of a twisted shape and production as large pieces [2]

Stanley Donald Stookey, a young researcher at Corning Glass Works, accidentally found glass ceramic while trying to make photography paper (bromide paper) by heat treating lithium disilicate glass and silver pieces residue in a furnace at 600°C. He mistakenly heated the furnace up to 900°C and found a piece of white solid material at furnace bottom while expecting to find molten glass there. When he threw this white piece of material on the floor, he realized that it didn't break into pieces or crack, which is what we would expect from normal glass. [4]

The first commercial glass ceramic was used in aviation industry for aircraft and missile nose cone towards the end of 1950s. These protective covers had to endure some tough conditions such as the corrosion effect of rain and atmospheric drag. The necessary factors to guarantee such resistance are as follows: homogeneity, low dielectric constant, low expansion coefficient, high endurance and high abrasion resistance. None of the available glass, metal and single-crystal materials –except hybrid ones- can meet all of these conditions alone. Glass ceramics are the outcome of the crystallization of certain glass types (often by using certain additive agents triggering the process). In fact, this is something that occurs randomly on glass surface and it is not normally a desired outcome in glass production. This crystallization can occur during waste glass phase and crystal phase in one or more points. Crystallization can range between 0,5% and 99.5% and often occurs between 30-70 percent. Controlled crystallization can have various effects on material- even some unusual ones.

Some basic characteristics of glass ceramic are as follows:

- It has lower density despite its similar characteristics to crystal ceramics,
- It is convenient for mass production thanks to glass forming techniques, easy to be processed and have low processing cost.
- It is possible to design its nano and micro structure for a certain application.
- It has a very low porous structure
- It combines many useful features in one structure.

Most of glass ceramics have lower hardness and elasticity

Table 1. Physical and mechanical specifications of Spinel, AlON, sapphire, glass ceramic and molten silica								
Material	Chemical composition	Density [g/m³]	Bending Resistance [MPa]	Young Module [GPa]	Knopp Hardness* [kgf/mm²]	Poisson ratio	Melting Temperature [°C]	Transmittence (μm)
Spinel	$MgAl_2O_4$	3,58 [9]	185-250 [9]	277 [9]	1645 [9]	0,26 [9]	2135 [9]	0,25-6,5 [10]
AlON	$Al_{23}O_{27}N_5$	3,69 [10]	300-700 [10]	320 [10]	1800 [10]	0,24 [10]	2150 [10]	0,22-6 [10]
Sapphire	Al_2O_3	3,97 [11]	1035 [11]	435 [11]	1900 [11]	0,27-0,3 [11]	2053 [11]	-
Glass ceramic	-	2,6 [12]	-	120 [12]	-	-	1350 [12]	-
Molten silica	SiO_2	2,21 [1]	48 [1]	70 [1]	600 [13]	0,17 [1]	1100 [13]	0,18-3,5 [1]
*Under 200 g of load								

module values than other ceramics used in armour production as well as other advantages such as low density and low cost [4]. Currently, Alstom Company produces lithium disilicate-based glass-ceramic, called TransArm, for transparent armour systems [2]. This material can easily be processed like amorphous glass and displays the characteristics of ceramic when crystallized [5]. This product has been developed especially for protective shields used during disposal of bombs [4].

The product called DiamondView™ by Schott Company is glass ceramic that has high ballistic resistance and is transparent at infrared wavelength for night vision. These ceramics have low working life costs since they are more durable than traditional glass-based transparent armor systems against thermal expansion-contraction loop and ultraviolet radiation [6].

2.2. Transparent Crystal Ceramic Armours

Crystal ceramics are used in armour production industry against today's advanced threats. Today there are three main types of transparent crystal ceramics used in armours: aluminium oxynitride (AlON), magnesium aluminate spinel (Spinel) and single crystal aluminium oxide (Sapphire) [2] (Table 1). Aluminium oxynitride and magnesium aluminate spinel are often preferred for laser use in military and space/aviation industries due to their strength, availability in large amounts and low costs [7]. All of above mentioned materials are able to protect against armour piercing bullets although they weigh almost the half of glass laminates. However, their relatively high cost and low availability are the most important obstacles for widespread use. The production of these materials will always be more costly than glass; however, reducing production costs and increasing the volume of production are likely to increase their applications in transparent armour systems [8]. Transparent crystal ceramics have certain advantages over other available transparent armour materials such as easy manufacturing, mechanical characteristics, high temperature performance and chemical strength.

Transparent polycrystalline materials are isotropic and the mixture of nitrogen with aluminium oxide makes it stable at spinel phase due to its crystallized structure. It is possible to produce complex shaped pieces by using traditional ceramic production techniques such as pressing, hot isostatic pressing and casting tape [2]. Today, γ-AlON and magnesium spinel are produced in large quantities and sizes. However, high production costs prevent them from replacing glass and some opaque ceramics for now [6].

2.2.1. AlON Ceramic Armours

Aluminium Oxynitride Al23O27N5 – AlON was developed by the researchers working in a company called Raytheon for windows and infrared missile nose cone in 1980s under the brand name "Raytran" [2]. The aim of the company was to develop a new material that has the same structural and optical characteristics as sapphire but can have lower production cost thanks to traditional powder processing techniques. Although the company produced cheaper missile nose cone and windows, the products could not reach desired sales figures partly due to inefficient investment

The spinel panels produced by TA&T Company for military units were tested by installing them on FMTVs (Family of Medium Tactical Vehicles).

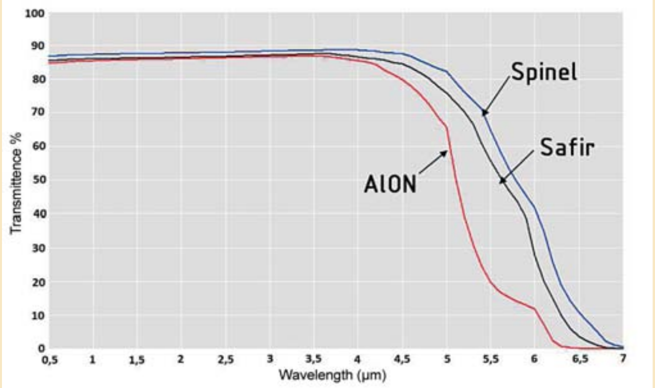


Figure 4. The comparison of optical transmittance of spinel, AlON and sapphire [10]

and marketing strategies and partly the problems with the popularity of the Raytheon Company. After the deal signed with Surmet Corp., this new company became the commercial manufacturer and supplier of AlON [14].

AlON is a transparent ceramic material that is permeable for the rays ranging from ultraviolet spectrum to mid wavelength infrared one and displays high resistance and toughness. It is also relatively light, stable until 1200^{0}C and resistant against oxidation and radiation [15]. The structural and isotropic transparency of AlON is due to its cubic crystal structure. Therefore, it is transparent even in polycrystalline form and can be produced by using traditional powder processing techniques [8]. Thanks to that, complex shapes can be manufactured in larger quantities and at lower cost than single-crystalline ceramics and polishing can be realized at lower costs compared to sapphire [14]. Unlike AlON, sapphire pieces are produced through the application of a technique using single crystalline growth when they are molten, which brings a disadvantage regarding the size of sapphire pieces (especially width and thickness) depending on production rate and cost. AlON can be produced more easily and at lower costs for thickness levels higher than 7.62mm, which is the standard size for sapphire panels available in the markets. Therefore AlON is superior to sapphire in terms of protection against handmade explosives and armour piercing bullets larger than 30 calibre projectiles (12,7mm, 14,5mm) [8].

Because of the above mentioned advantages of AlON, it is convenient to use this material for the production of infrared glass, radar domes, lenses and transparent armours [8]. Its resistance to scratching is higher even than strong coatings such as scanner glass used in supermarkets thanks to its high toughness level [16]. Infrared nose cones of high speed missiles should resist against serious thermal shocks they will be exposed during flight and keep its transparency despite the corrosive effects of rain and sand. The transparency of glass-based armours decreases during outdoor use due to the scratches caused by wind, dust, sand and stones. The tests conducted to imitate the corrosion effect of natural sand revealed that transparency of glass-based armours decreased by 23 percent while AlON had no change in its transparency level [7]. It is necessary for outer layers of light transparent armours to have high resistance and toughness levels. Lighter ballistic laminates can be designed by using thin AlON panels that have high fracture resistance [17]. When compared to glass / plastic laminates in terms of their resistance against armour piercing bullets, AlON was found to be 50 percent lighter and thinner although it has the same protection performance. When considered from the perspective of market share, the best potential markets for AlON are transparent armor applications for land, sea and air vehicles [14].

2.2.2. Spinel Ceramic Armours

Spinel ($MgAl_2O_4$) is a common material for transparent armours and optical applications due to their high toughness, lightness and optical characteristics at broad spectrum. In terms of transparency, Spinel is permeable for the spectrums ranging between 0.19 μm and 6.0 μm and more transparent than AlON and single crystalline sapphire. In addition, it is optically more isotropic than sapphire and has higher heat stability than AlON [9]. Since spinel has superior optical characteristics, it can be used in sensor applications such as missile nose cone [16]. The main characteristics of spinel are as follows:

- It has better resistance although it is 50 percent lighter and thinner than ballistic glass armours
- Crack propagation is convenient for multiple impacts.
- It is highly resistant against erosion caused by projectile at the moment of impact and also against scratching and impacts due to external effects.
- Since it is highly transparent for mid wavelength infrared rays, it has better night vision performance [18].

Although the production techniques of spinel are the same as AlON's, its raw materials are cheaper and more easily available. In addition, heat treatments applied during production are lower. Despite all the investments made so far, transparent spinel panels are mostly manufactured for research purposes. Its structural characteristics are also similar or less advantageous than sapphire and AlON [1].

Spinel products are manufactured by two leading American companies called "Technology Assessment and Transfer (TA&T)" and "Surmet Corporation" [16]. TA&T Company uses vacuum hot presses of various sizes; namely 30 tones, 250 tones, 600 tones. It is possible to produce spinel panels of 45.7 mm in diameter or the ones with a size of 43.2 cm x 76.2cm.

Figure 5. Transparent sapphire covers of target acquisition system of an F-35 aircraft [20]

Table 2. Physical and Mechanical Specifications of PMMA and PC [24]

Material	Molecular Formula	Density [g/m³]	Tenacity [MPa]	Young Module [GPa]	Poisson Ratio	Melting Temperature [°C]	Thermal Conductivity [W/m.K]	Permeability (%)
Polimetilmetakrilat (PMMA)	$(C_5O_2H_8)_n$	1,15 – 1,19	47 – 79	1,8-3,1	0,35-0,4	130	0,167-0,25	80–93
Policarbonate (PC)	$(C_{15}O_2H_{16})_n$	1,20-1,22	55-75	2,0-2,4	0,37	267	0,19-0,22	90

Pressureless sintering has also the potential for production in large quantities at low cost. Researchers are now working on developing new shaping methods to reduce costs depending on the size of the piece manufactured. The production of missile nose cones and small scale bomb heads is the most important potential area of application [9]. The spinel panels produced by TA&T Company for military units were tested by installing them on FMTVs (Family of Medium Tactical Vehicles). TA&T also developed very light armour solutions within the scope of this project [18].

2.2.3. Sapphire Ceramic Armours

Sapphire is a single crystalline transparent ceramic. It has rhombohedral crystal structure, so especially its anisotropic and crystallographic direction is variable. Sapphire is the oldest transparent ceramic material in terms of its applications and production, and there are currently a large number of producers. However, it is one of the most expensive transparent armor materials due to high manufacturing temperatures and high processing and polishing costs. The formation of single crystalline ceramics and difficulties in processing seriously limits mass production and application areas [15]. Although sapphire has high resistance levels, it has certain disadvantages such as the use of large induction furnaces and high mold processing costs. In addition, the transparency of products depends on the quality of surface polishing process. Nevertheless, sapphire producers have been able to develop advanced features during the competition they had with other glass and ceramic alternatives and increased their market share considerably [15]. The applications of sapphire can be listed as follows:

- Infrared applications (radiometry, guided missiles, gas analysis, medicine, safety)
- High pressure and shock loading applications (pressure and heat chamber windows for chemical applications)
- Optical applications (in optical devices used within the range between 250-5000 wavelength - from ultraviolet to infrared)
- Scratch-free watch glasses [19].

Saint Gobain Group produces transparent sapphire called Saphikon by using a promising technique called edge-defined growth. Although the transparency of the sapphire produced is relatively low, it is both cheaper and has the same toughness and corrosion resistance values as other sapphires. Wide windows are produced by using optical polishing to meet commercial demands. The company can produce panels with a thickness of 0,43″ (10,9 mm) and 12″ x 18.5″ (30,5 cm x 47 cm) as well as thick and simply curved ones. In addition, the company became commercialized to meet the needs of new generation F-35 and F-22 aircraft [16]. The transparent covers of electro-optical target acquisition system of F-35 Lightning II aircraft shown in Figure 5 below are made of sapphire [20].

3. Polymeric Armour Systems

The demand for polymer-based light and transparent armour systems against mild gun effects in surveillance and control systems is increasing day by day. Transparent armour systems are basically composed of two structures known as front and back layer. Considerable amount of synergy is generated between these two plates and the nature of impact behaviour depends on the reaction of the target. When these multi-layered systems are compared to classical monolithic armours such as steels and aluminium alloys, they have clear advantages in terms of weight. Being generally ceramic-based, the front layer is used to decelerate and split the projectile and to spread the impact energy to back layer aerially and temporally by causing a crack. Back layer is not only used to ensure structural unity but also to store impact energy and to stop bullets and ceramic pieces. Therefore, the back layer should be made of polymeric materials to ensure energy absorption through plastic deformation [21]. Polymethyl methacrylate (PMMA) and polycarbonate (PC) – types of thermoplastic material- and polyurethane (PU) are polymeric materials used is transparent armour applications. PMMA structures are often used in transparent armour systems due to their distinctive characteristics such as pressure sensitivity, high strain rate depending on resistance, low density, dimensional stability, transparency and high resistance. At high tension rates, PMMA displays fragile / ductile transition that results in adiabatic shear bands [21/22]. Polycarbonate structures, which have high ductility at room temperature, undergo plastic deformation during static and dynamic loading. During deformation, most of the energy absorbed turns into thermal energy, which provides high impact resistance depending on bullet penetration mechanism. [23]. In addition, it is possible to form systems where these materials are used as back layer. Especially, the structures where PC layers are separated by thin PU rubber systems are effective in spreading impact energy aerially and temporally [21]. Apart from these structures, amorphous glassy polymers and nano composite polymers are used as intermediate and back support layers especially in military vehicles. Table 2 displays physical and mechanical characteristics of PMMA and PC – polymeric armour materials examined within the scope of this study. Figure 6 displays the graphics where optical transmittance rates are compared [24,25]. Above mentioned information clearly shows that these materials have a very wide range of applications. Since transmittance of PMMA and PC are

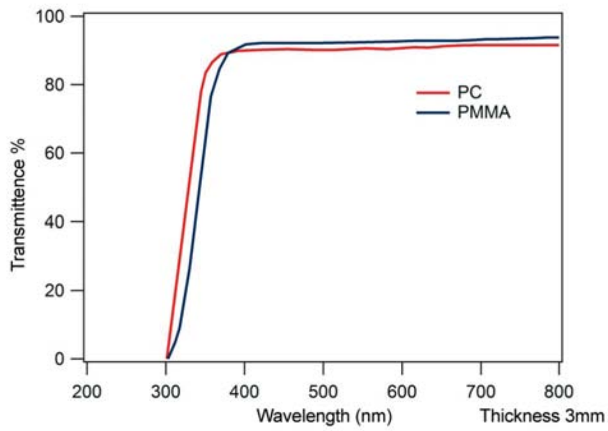


Figure 6. The comparison of transmittance: PMMA and PC [25]

similar after 300 wavelengths, they are used instead of quartz in spectrometer incubators, which require high transmittance. The most important disadvantage is low resistance against fractures. However, this weakness can be cured by using PVD, CVD or SOLJEL coating (optical organoceramic coating) techniques.

3.1. PMMA Based Transparent Armours

PMMA is a polymeric material having high sensitivity towards mechanical reactions and displaying unique viscoelastic behaviour. It is manufactured through the polymerization of methyl methacrylate, which is a type of glassy thermoplastic polymers. PMMA was first produced by Rohm and Haas Company in 1933. The leading PMMA brands today are Altuglas, Plexiglass and Diakon. Polymers have excellent optical characteristics and very close to the transparency rate of glass and permeates 92 percent of light. Structurally speaking, they are resistant against atmospheric conditions, have low water absorption, and high dimensional stability and mechanical resistance. Thanks to these characteristics, they are preferred for engineering applications rather than glass. Depending on compositions, dimensions, glass transition temperature and molecular weights, polymers is often used in many industries such as automotive, cosmetics, medicine and defence [2].

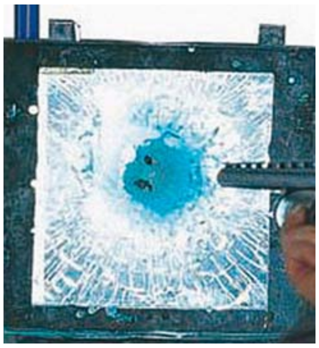


Figure 7. The display of PC-based transparent armour after fire test [25]

Semi-static pressure measurements show that PMMA's dependency on yield stress / tension ratio is more apparent. Despite having a fragile structure, it has higher ballistic impact performance in proportion with bullet impact speed and plate thickness [3]. PMMA can display different deformation resistance than PC for the same bullet impact and similar impact resistance to fracture mechanism. PMMA is able to form bonds with side chain carbonyl ester groups. The molecular mobility of these side chain groups is quite flexible at ambient temperature. Despite this situation, short chain segments freeze when mechanical deformation speed increases and reaches a threshold value. In this situation, under semi-static mechanical deformation, SIDE CHAIN molecules – which cannot contribute to ductility feature of PMMA- provides the desired toughness for high speed impacts instead [24].

3.2. PC-Based Transparent Armours

Polycarbonate (PC) is an important material preferred for structural engineering applications such as armour systems, police riot shields and for modern manufacturing sectors where transparent polymeric structures with high impact resistance are required. It is easier to process, mold and shape this material through heat treatment, which are called "polycarbonates" since they have functional groups linked by carbonate groups (-O-CO-O-) in long molecular chains. The characteristics of polycarbonates are quite similar to polymethyl methacrylate (PMMA), except being stronger and more expensive.

The most common polycarbonate type is the one having polymer chains formed by carbonate groups linked by Bisfenol-A groups. These types of polycarbonates light transmittance indices are

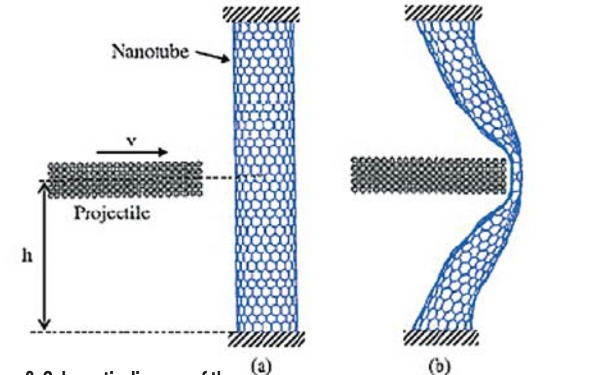


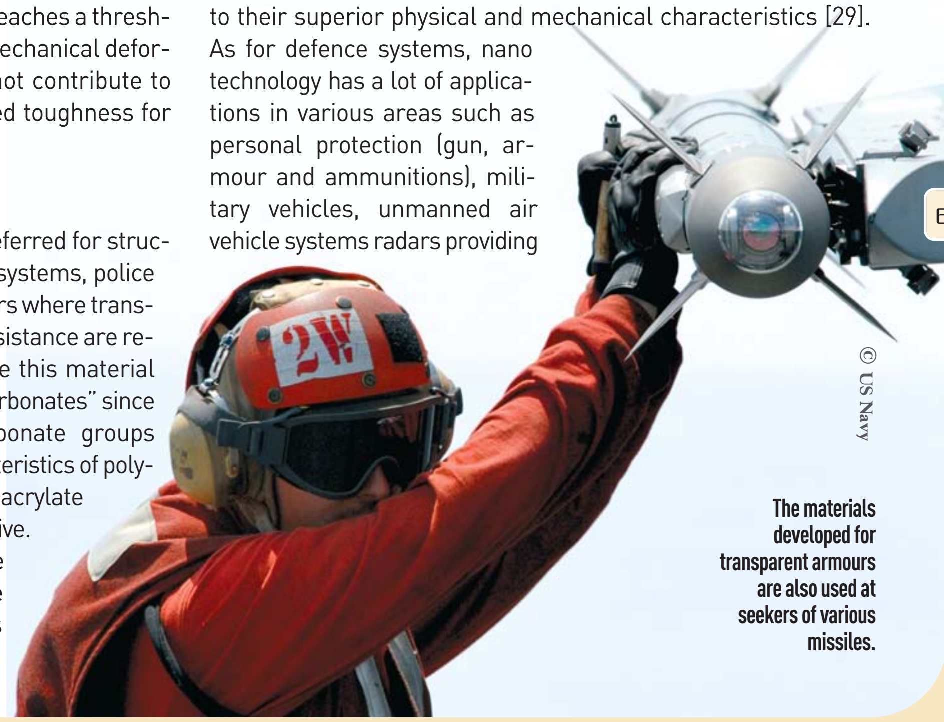
Figure 8. Schematic diagram of the interaction between the bullet and carbon nanotube [29]

(90 percent +/- 1) with high strength properties. They are used in the products such as shatterproof and light reflecting glass developed for protection purposes especially in buildings requiring security precautions. Among other products made of polycarbonate are glasses, ophthalmic glass for sunglasses, compact disc and headlight glass for cars. CR-39 is a special polycarbonate material that has optical and mechanical advantages and is often used in ophthalmic glass production. Since it is highly resistant to UV (Ultra Violet) rays, it is used as coating material in construction sector as well. In addition, PC is commonly used in visors integrated into the helmets of fighter's pilots due to the above mentioned superior characteristics.

The factors affecting impact resistance of polycarbonates are temperature, strain rate and notch diameter, so it is necessary to focus on these factors to improve the mechanical behaviour of the structure. The studies reveal that the resistance of polycarbonate increase from 150 MPa to 400 MPa within a strain range of 4000-8500 s^{-1}. Tenacity of polycarbonate measured during semi-static range of stress is 65 MPa. In armour systems, the damage on impact point by bullet causes a decrease in impact resistance. This damage occurs due to weight and shape characteristics of bullet such as kinesthetic energy. Thanks to the movements of main chain molecules of polycarbonates, the structure ductility and molecular mobility enables effective distribution of impact energy when polymer is exposed to strong impacts (Figure 7) [27,28].

3.3. Nano Composite Polymers

The studies on polymer matrix nano composites show that especially carbon nano tubes will soon be used in many fields due to their superior physical and mechanical characteristics [29]. As for defence systems, nano technology has a lot of applications in various areas such as personal protection (gun, armour and ammunitions), military vehicles, unmanned air vehicle systems radars providing



The materials developed for transparent armours are also used at seekers of various missiles.

communication and intelligence, portable motion detectors, biochemical sensors and quick reporting systems [30].
Back support layer and resistance of the layer against impacts is an important feature. The studies reveal that carbon nano tube reinforced armours are superior to other traditional armour systems in terms of resistance. Reducing the weight carried by soldiers and armour density are the most important factors increasing the mobility and defence ability [31]. The resistance of carbon nano tubes – which has a value of 13-53 GPa- protects personnel from external effects such as bullets and shrapnel. In addition, it has the ability to reach 152 GPa toughness value, which is higher than diamond, when correct pressure is applied. Due to this characteristic, a bullet that reaches nano tube deviates or is deformed. In order to absorb more energy, carbon nano tubes with higher diameters are used. Carbon nano tubes have the ability to return into their original shape in a very short time after the interaction with the bullet without being deformed and fractured (Figure 8) [32].
The resistance and ballistic performances of polymer matrix multi-walled carbon nanotube reinforced structures are very high. Their superior mechanical characteristics, low density and wide surface area make these single-walled (SWCNT) and multi-walled (MWCNT) carbon nano tubes ideal materials for polymer matrix advanced technology transparent armour reinforcement [33]. In such structures, blending aromatic and low and high molecular weight polymers increases the resistance of composite along the main chain [34].

4. Conclusions

Within the scope of this study, the expectations from current transparent armour systems, the important considerations in armour material selections and commonly used ceramic and polymeric transparent armour systems were examined in detail. Armour materials are important defence technology materials commonly used in personnel protection and land/air/sea vehicles due to their certain ballistic advantages such as high endurance, hardness and toughness as well as other superior characteristics such as lightness, optical transparency and resistance against heat and scratching. The materials developed specifically for transparent armour systems in military practices will have wide range of use in civil contexts in the fields of energy industry, laser, and video and LCD applications. The development of lower cost production methods and various advanced technological materials will reduce the cost of transparent armour systems, which will result in wider areas of application.

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