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REVIEW

Aramid fibre as potential reinforcement for polymer matrix composites: a review

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Abstract
For the manufacturing of composites, researchers all over the world have moved from commercially available glass fibres to aramid fibres in recent years. The low density, ease of availability and high basic intensity of aramid fibres drew the attention of researchers and academicians alike. As a result, considerable progress has been made in the development of aramid fibre-reinforced composites for various industrial applications over the last decade. As a result, in-depth awareness of this fibre and its composites is essential right now in order to achieve better results. The emphasis of this study was on recent advancements in aramid fibre-reinforced polymer matrix composites. In this study, the manufacturing, surface treatment of fibres and possible applications are addressed. The advantages, disadvantages and real-time successful industrial components of this fibre are also briefly explored.

Keywords Polymers · Composites · Aramid fibre · Processing · Surface treatments · Application

1 Introduction

Polymer matrix composite (PMC) is a well-known composite material with desirable characteristics such as low density, high stiffness, high tensile strength and corrosion and chemical resistance [1]. Composites like these have been used in a variety of industries, from cars to more sophisticated areas like aeronautics and robotics [2]. Thermoset (epoxies, polyester resins, vinyl esters, bismaleimide and polyamides) and thermoplastic (polyesters, polypropylene, polyphenylene sulphide (PPS), polyether ether ketone (PEEK) and liquid crystal polymers) matrices are used to fabricate polymer composites [3]. Fibre reinforcements are frequently used to improve the performance of PMC because they have excellent properties such as high strength, high modulus, low coefficient of thermal expansion and chemical inertness [4]. Fibres are fabrics with a high aspect ratio, meaning their effective diameters are many times larger than their dimensions. Composites are reinforced with both synthetic and natural fibres [5]. Nylon, aramid, teflon and polyester fibres are commonly used in synthetic domain glass [6]. Jute, ramie, sisal, hemp, coir and basalt fibres, on the other hand, are often found in natural settings. Thanks to their high toughness, low density, high specific heat power and excellent electrical properties, aramid fibres have a large number of applications in industry [7].

Aramid fibre was the first organic fibre with sufficiently tensile modulus and strength to be used as insulation in specialised composites. On a weight-for-weight ratio, they have far superior mechanical properties to steel and glass fibres. Heat and flame resistance are intrinsic properties of aramid fibres, which are maintained at high temperatures [8]. According to the US Federal Trade Commission, the term 'aramid' refers to fibres of the aromatic polyamide form in which at least 85% of the amide bonds (CO–NH) are bound directly to two aromatic rings. The classification of the polymer is often based on the structure of these bonds as para or meta [9, 10]. Figure 1 shows the aramid (aramide) fibre (a) molecular structure, (b) yarns and (c) woven cloth commercially used.

The properties of the resulting fibres change dramatically as the aliphatic carbon backbone is replaced with aromatic groups. The first fibre of this kind was DuPont's Nomex, which was introduced in the 1960s. This yarn has a low tenacity but is nonflammable and is commonly used for fireproof fabrics, electric insulation and other applications [11, 12, 13]. However, aramid fibres (also known as Aramid

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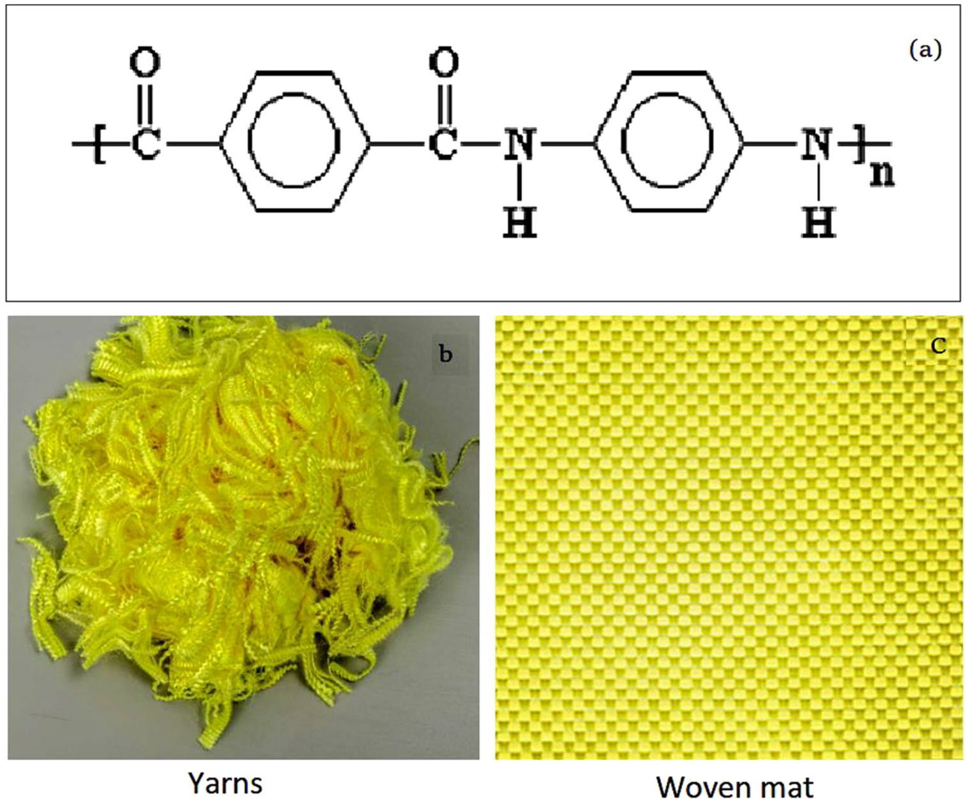


Fig. 1 Image of **a** molecular structure of aramid fibre, **b** fibre yarns and **c** woven mat (source: internet)

by DuPont) with chains containing p-disubstituted benzene rings emerged only a few years later. These fibres have excellent mechanical properties in addition to good thermal stability [14]. Their exceptional ability stems primarily from the anisotropy of their superimposed substructures, which exhibit fibrillar, pleated, crystalline and skin–core properties. Due to the formation of hydrogen bonds, aramid fibres are polar. This property improves aramid fibres' wettability and makes them more chemically active than UHMWPE fibres [15]. On the other hand, in the case of high temperature and humidity, this is also responsible for the hydrolytic degradation of aramid fibres [16]. Aramid fibre-based UD composite fabrics are reinforced with high-performance aramid fibres. Aramid®, Zylon® or PBO fibres and M5® fibres are the most widely used fibres. The following are some of the most typical characteristics of aramid fibres [17]. High toughness and high strength-to-weight properties Abrasion and cutting resistance are good. Chemical solvent resistant, but susceptible to certain acids, bases and chlorine, under normal conditions, it is nonconductive, but it is susceptible to hydrolytic degradation when exposed to elevated temperatures and humidity. At high temperatures, the cloth maintains its integrity. When exposed to UV radiation, it is susceptible to deterioration [18, 19, 20].

1.1 Advantages of aramid fibre

Aramid main advantages are high strength and low weight. Like graphite, it has a slightly negative axial coefficient of thermal expansion, which means aramid laminates can be made thermally stable in dimensions. Unlike graphite, it is very resistant to impact and abrasion damage. It can be made waterproof when combined with other materials like epoxy. It can be used as a composite with rubber retaining its flexibility. High tensile modulus and low breakage elongation combined with very good resistance to chemicals make it the right choice for different composite structural parts in various applications. It is a para-aramid fibre with tensile strength of about 3620 MPa and relative density of 1.44 g/cm^3. This density is relatively smaller than glass fibre of 2.54 g/cm3. Aramid maintains its strength and resilience down to cryogenic temperatures (− 196 °C) unlike glass and carbon fibres. Moreover, aramid fibre exhibits similar tensile strength to glass fibre, but can have modulus at least two times as great. Aramid is very tough allowing significant energy to absorb with in molecular structure. It is having good resistance to abrasion and cutting; it does have no melting point and resistant to thermal degradation and flammability. Moreover, It has good fabric integrity at elevated temperatures [21, 22, 23].

1.2 Disadvantages of aramid fibre

There are a few drawbacks to Aramid. Aramid composites are more vulnerable to the atmosphere than glass or graphite composites because the fibres contain moisture. As a result, it must be used in conjunction with moisture-resistant fabrics such as epoxy systems. Compressive properties are also lacking. As a result, aramid is not used in bridge construction or anywhere else where resistance is needed. Aramid fibres are often difficult to cut and grind without specialised machinery (e.g. special scissors for cutting, special drill bits). Finally, they corrode and are degraded by ultraviolet radiation. As a result, proper coating is needed [24, 25].

1.3 Application of aramid fibre

There are two types of uses for aramid fibre. The first is insulation of composites such as sporting goods, aircraft and military equipment. The second is a fabric used in garments, such as fire prevention clothing or bulletproof vests. The following are few more in-depth aramid applications: sailcloth, snowboards, safety gloves, caps, body armour, filament wound pressure vessels, flame and cut resistance apparel, asbestos repair, cords and wires, optical fibre cable networks, jet engine enclosures, tennis strings and hokey sticks, wind instrument reeds and tyre and rubber products protection [26–28, 29].

2 Processing of aramid fibre PMC

2.1 Fibre weaving

Weaving is the process of crossing and interlacing two sets of straight yarns, the warp and the weft, at right angles to each other. Warp yarns are used in the lengthwise direction, while weft or filling yarns are used in the width direction, and the fabric produced is called woven fabric [30]. A weft—the yarn that runs across the width of the cloth—and a warp—the yarn that runs across the length of the loom—make up woven fabrics. The yarns are all intertwined. The selvedge [31] is the side of the cloth where the wefts are double backed to form a non-fraying lip. The warp and weft in a plain-woven cloth are aligned to create a basic criss-cross pattern. This weave is sturdy and long-lasting. The crossing of the weft and warp in a twill weave cloth is offset to create a diagonal pattern on the fabric's surface. The warp and weft threads in a satin woven cloth are arranged in a complex way, allowing longer float threads to run over the warp or weft. The long floats prevent light from scattering and breaking up on the thread, as it does on a simple weave. Satin is the name given to a smooth, lustrous surface created by reflected light.

The back side is still dull and non-shiny. Knitting is a process of knitting in which yarns are shaped into loops, each of which is usually only released after a succeeding loop has been formed and intermeshed with it, resulting in a stable ground loop structure. Knitting machines or knitting needles are used to create these materials, which are made up of single or several lengths of continuous yarn. Weft-knitted fabric is created by looping long lengths of yarn together, which can be done by hand or by machine. Rows of yarns stretch through the cloth. Socks, t-shirts and sweaters are made from this stretchy and lightweight fabric. The loops in warp knitted fabric interlock vertically along the fabric's circumference. They are non-laddering and stretchy. This machine-made fabric is used in swimwear, socks and textiles. Figure 2 depicts the different types of weaving patterns that can be used to make fibre cloth [32–34, 35].

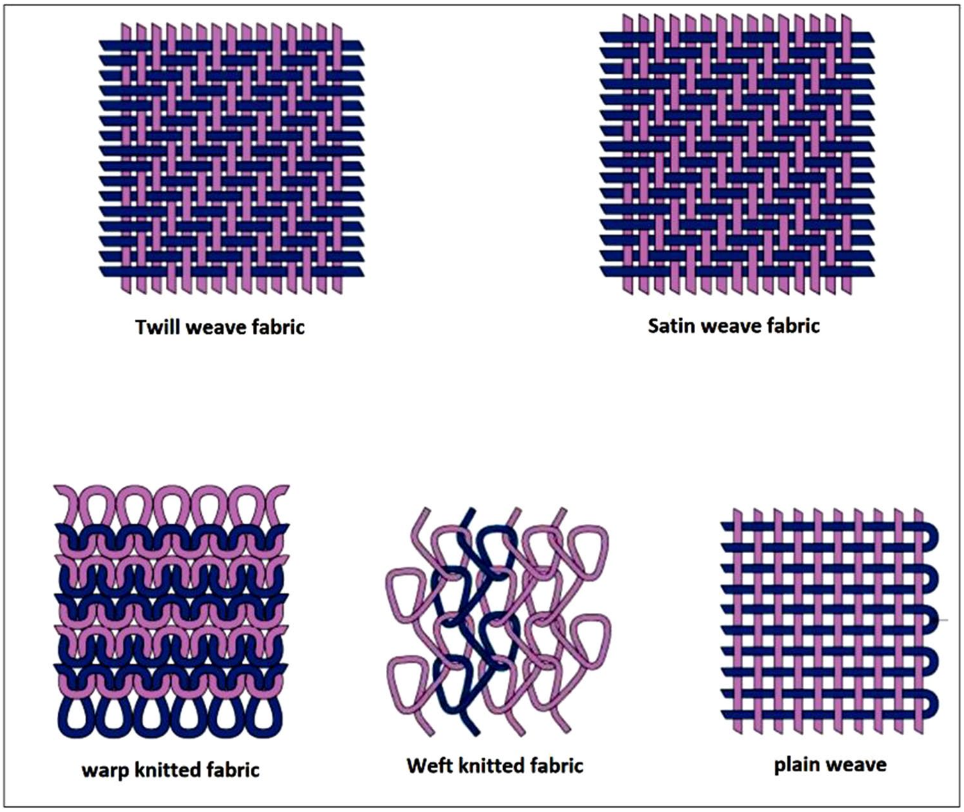
2.1.1 Shuttle looms

A loom is a machine that weaves threads into fabric. The power loom was a motor-driven loom that automated the weaving process and eliminated the need for humans to supervise the process [36]. The initial version had flaws that needed to be fixed. Power looms functioned in a similar way to handlooms [37]. Foot pedals raised and lowered the warp (tightly strung threads) on handlooms, while the weft (weaker threads) was drawn in between the warp threads to create fabric. This simple method was preserved on power looms, but the power source used to draw the warp threads was replaced with steam power, minimising the ability necessary to weave the fabric [38]. The warp beam, heddles, harnesses, shuttle, reed and pick up roll are the key components of the loom. Yarn processing on the loom involves operations such as shedding, picking, battening and taking-up [39].

2.1.2 Shedding

Shedding is the process of lifting the warp yarns to create a loop into which the shuttle will insert the filling yarn. The shed is the vertical space between the warp yarns that are lifted and those that are not [40]. The heddle or heald frame, also known as a harness, on a modern loom performs basic and complex shedding operations automatically. A rectangular frame is connected to which a string of wires such as heddles or healds are attached. The yarns are threaded into the eye holes of the heddles, which are suspended from the harnesses vertically. The weave pattern specifies which harness is in control of which warp yarns, and the amount of harnesses used is proportional to the weave's complexity. Dobbies and a Jacquard head are two traditional ways to handle the heddles [41, 42].

Fig. 2 Fibre weaving patterns



2.1.3 Picking

The shed is formed as the harnesses lift the heddles or healds, which raise the warp yarns. A small carrier unit called a shuttle is used to insert the filling yarn into the shed. To allow passage through the shed, the shuttle is usually pointed at both ends. The filling yarn is wrapped onto a quill, which is then placed in the shuttle in a conventional shuttle loom. As the shuttle flies around the loom, the filled yarn appears from a hole in the shuttle. A pick is a single crossing of the shuttle from one side of the loom to the other. The shuttle weaves a selvage on either side of the cloth as it runs back and forth around the shed to save it from wrinkling [43, 44, 45].

2.1.4 Beating in

The shuttle passes through holes in another frame called a reed as it pushes around the loom, setting down the fill yarn (which resembles a comb). The reed presses or battens each loading yarn against the portion of the cloth that has already been shaped during each picking process. The fell is the point at which the fabric is made. Conventional shuttle looms will pick between 150 and 200 picks per minute [46]. The standard examples of different weaving processes (a) shedding, (b) picking and (c) beating in are seen in Fig. 3.

2.2 Fibre surface treatments

Surface treatment is the method of using chemicals to improve the surface compatibility of second phase additions of resins. Surface modulation increases the adhesion of second phase contributions to the matrix, particle dispersion on the matrix and cross-linking, both of which increase mechanical properties. In general, the majority of second phase additions are not biological in nature and lack functional groups on their surfaces. Because of their poor compatibility, these substances can become distinct when applied to the resin. This will have an effect on the composites' mechanical, thermal and morphological properties. Chemical treatments such as chemical etching, chemical surface grafting and polymerisation modification are typical methods of surface modification [47, 48].

2.2.1 Alkaline treatment

One of the most popular treatments is alkaline treatment. To begin, this treatment breaks down the plant fibre bundles to release the individual fibres. Smaller particles with a higher aspect ratio and a rougher topography are produced, which improves fibre/matrix interactions. NaOH has been extensively used in this system to dissolve the ester linkages of the polyester backbone, resulting in hydrophilic hydroxyl and

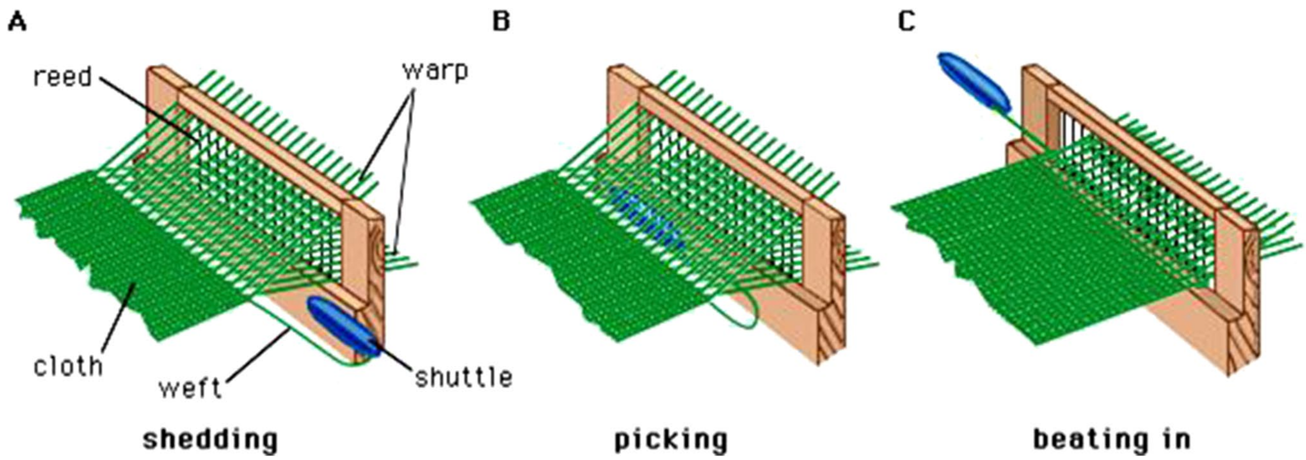


Fig. 3 Images of weaving processes (source: internet)

carboxylic groups [49]. Figure 4 depicts a standard alkali treatment on the surface of an alfa fibre.

2.2.2 Silane treatment

Synthetic hybrid inorganic–organic compounds called silane coupling agents are used to promote adhesion between dissimilar materials. They are effective at promoting adhesion in a variety of materials, including ceramics, metals, polymers and composite materials. Synthetic hybrid inorganic–organic compounds called silane coupling agents are used to facilitate adhesion between dissimilar materials. They are effective at facilitating adhesion in a variety of materials, including ceramics, metals, polymers and composite materials. The silane binding agent reacts chemically with non-silica-based materials to form a long-lasting bond. When two separate materials are bonded together, the interface between them becomes a complex field of chemistry in which surfaces must be changed to create ideal heterogeneous conditions or to integrate the bulk properties of different phases into a uniform composite structure. The silane treatment increases the mechanical strength of composite materials, as well as the properties of adhered joints and surface chemistry. Furthermore, a bonded joint that has been prepared with silane prior to use can withstand more extreme environmental conditions, such as high humidity and temperature shocks, than one that has not been treated [50, 51, 52].

Silane chemistry involves two distinct functional groups that can react with both inorganic and organic matrices, such as ceramics and resins. As a result, they can be used to bind dissimilar materials as coupling agents. Silanes can bind inorganic and organic materials together. X-(CH2) n-Si-(OR)3 is the general formula for a functional silane coupling agent, where X is an organofunctional group that reacts with an organic resin, -(CH2)n– is a linker group and

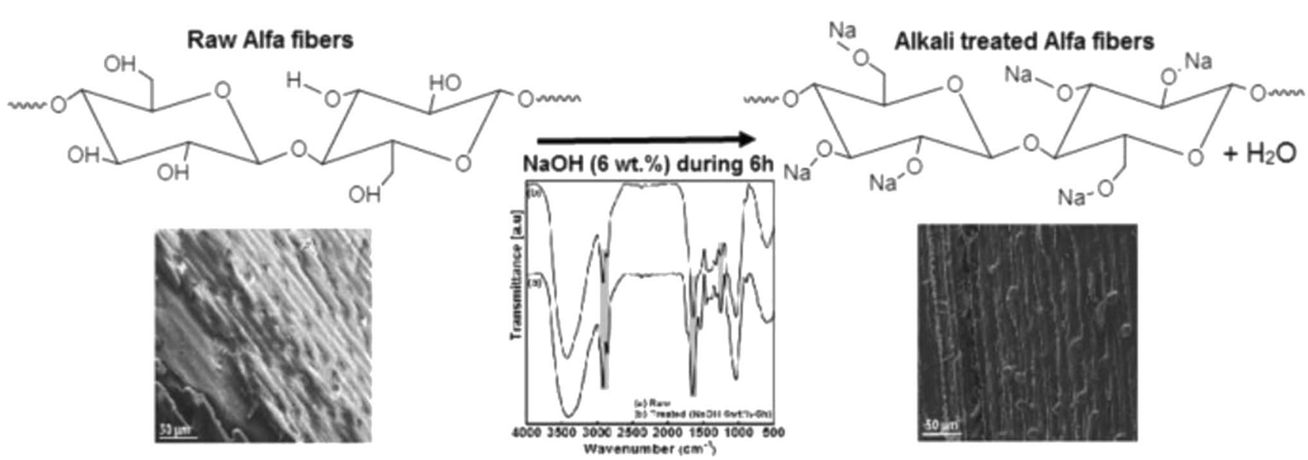


Fig. 4 Alkali treatment on fibre [49]

-OR is an alkoxy group. Until reacting with the substrate's surface hydroxyl groups, the alkoxy groups are activated by hydrolysis (SiOR SiOH). After treatment, Fig. 5 depicts a standard silane-treated fibre surface [53].

2.2.3 Acetylation treatment

Acetylation is a chemical reaction in which the acetyl function group is introduced into natural fibres. This procedure is applied to fibres after they have been bleached or alkali-treated, and will break down hydrogen bonds in cellulosic hydroxyl groups, making them more reactive. The hydroxyl groups are then substituted by a hydrophobic acetyl group (CH3CO), causing the fibre's hydrophilic form to transition to hydrophobic. Acetic anhydride, toluene and a limited volume of catalyst perchloric acid are the most often used ingredients for this treatment, which is carried out at 60 °C for 1–4 h. As a result of this treatment, the moisture rate of the fibre is reduced, and the dimensional stiffness of the composites is improved [54]. Figure 6 depicts a standard acetylation reaction on the surface of a fibre.

2.2.4 Benzoylation treatment

Benzoylation is a vital step in the organic synthesis process. In fibre treatment, benzoyl chloride is most commonly used. It contains benzoyl (C6H5C = O), which is responsible for the treated fibre's reduced hydrophilicity and increased contact with the hydrophobic PS matrix [55]. Figure 7 depicts the reaction between the cellulosic hydroxyl group of the fibre and benzoyl chloride.

Fibre benzoylation increases fibre–matrix adhesion, increasing composite efficiency, reducing water absorption and enhancing thermal stability. Surface treatment

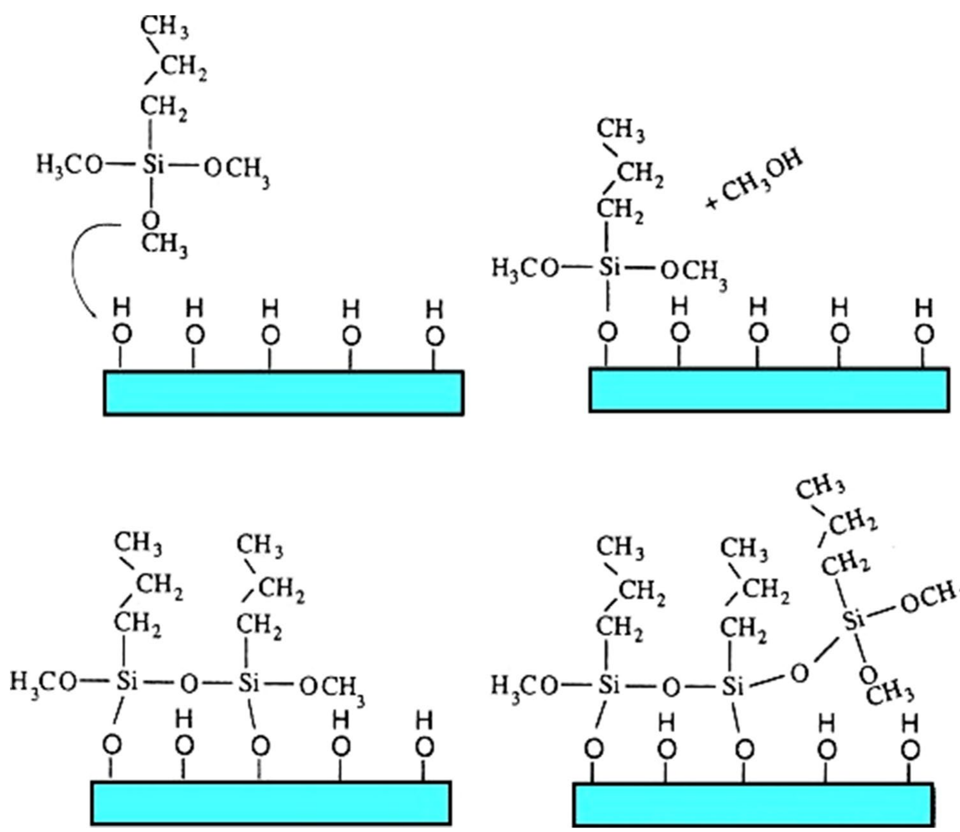


Fig. 5 Silane treatment on fibre's surface (source: internet)

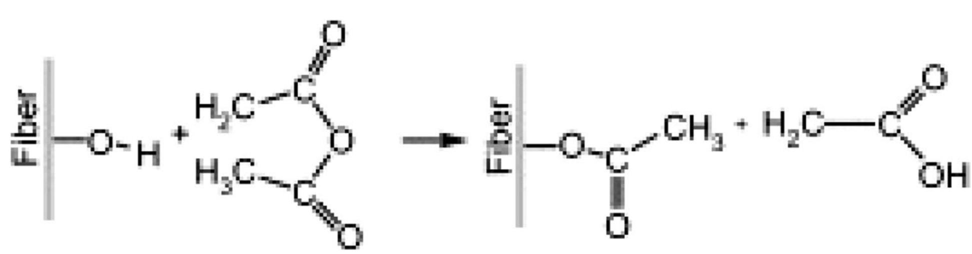


Fig. 6 Acetylation reaction on fibre surface (source: internet)

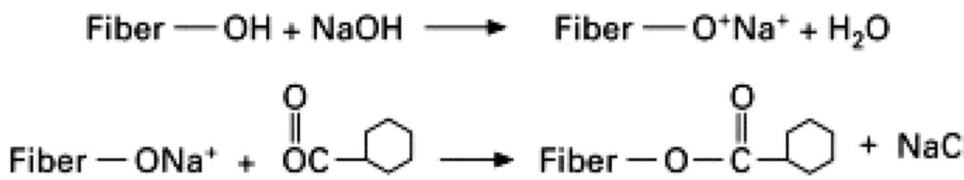


Fig. 7 Benzoylation of fibre (source: internet)

of sisal fibres was done with NaOH and benzoyl chloride (C6H5COCl) solutions. The thermal stability of treated fibre composites is found to be greater than that of untreated fibre composites. Flax fibre and PE matrix interfacial adhesion is improved by the procedure. The fibre is then alkaline pretreated to enable the hydroxyl groups of the cellulose and lignin in the fibre, and then suspended for 15 min in a 10% NaOH and benzoyl chloride solution. After that, the extracted fibres are soaked in ethanol for 1 h to extract the benzoyl chloride, then washed and dried in an oven at 80 °C for 24 h [56].

2.3 Composite making techniques

2.3.1 Resin transfer moulding

Using low viscosity thermoset resins and continuous fibres, the resin transfer moulding (RTM) technique was used to manufacture composite parts for high volume output net form structural parts. This chapter explains how to solve the complexities of RTM, which have resulted in a variety of variations over the past two decades to meet a specific need. Due to the effects of inherent differences in the materials and process parameters, the component quality generated by RTM varies.

Distance monitoring channels, deformation of fibre structure during draping, macro void formation, micro void formation, transverse flow in the thickness direction and dual scale fibre structure in a perform have all been established and addressed during the fibre preforming or mould filling stages of RTM [57, 58]. Figure 8 depicts a traditional composite manufacturing resin transfer moulding procedure.

2.3.2 Vacuum-assisted resin transfer moulding

The vacuum-assisted resin transfer moulding (VARTM) process is a closed-mould method for producing high-performance, large-scale fibre-reinforced polymer (FRP) parts at a low tooling cost. To make a composite, a low viscosity (100 to 1000 cP) polyester or vinyl ester resin is typically mixed with fibreglass fibres. In most cases, the process can produce composites with a fibre volume fraction of 40–50%. The resin-to-fibre ratio is important for determining the overall strength and performance of the final part, with mechanical strength being most influenced by the type of fibre reinforcement. Corrosion tolerance, heat distortion temperature and surface finish are all determined by the form of resin used. Due to the small pressure difference given by the vacuum pump, the resins used in this process must have low viscosities. Carbon fibre and other high-performance fabrics can also be used. However, they are used less often and are mostly for the production of high-end components [59]. The vacuum-assisted resin transfer moulding method [60] is depicted in Fig. 9.

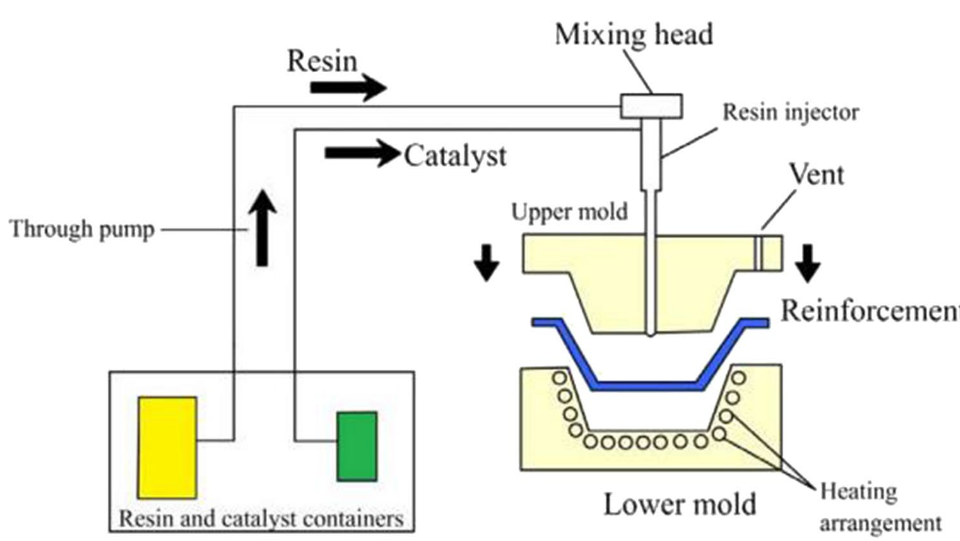


Fig. 8 Resin transfer moulding setup (source: internet)

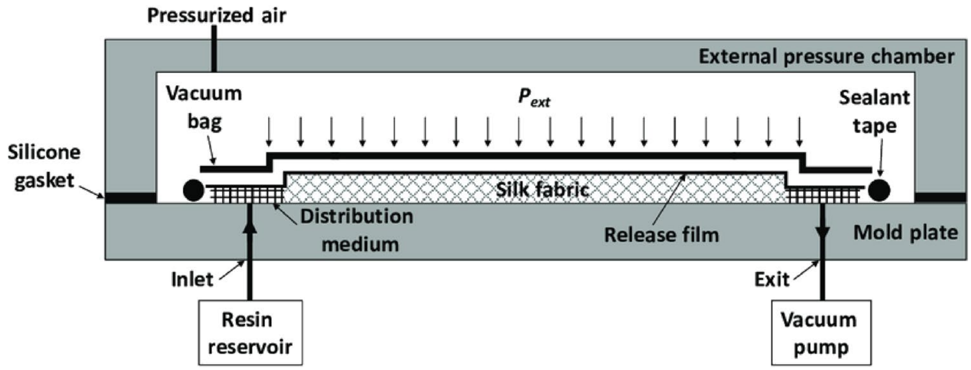


Fig. 9 Typical vacuum-assisted resin transfer moulding [60]

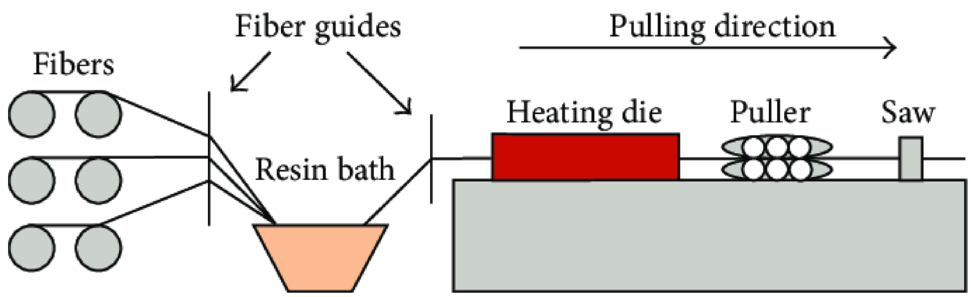


Fig. 10 Pultrusion composite making [62]

2.3.3 Pultrusion

Pultrusion is a continuous process for producing composites with consistent cross-sections or structural profiles with long lengths. Figure 10 depicts a standard pultrusion route used to create composites. Because of its constant, automated and high-production design, it is commonly used in the composites industry. The reinforcing components, such as fibres or knit or braided strands, are impregnated with resin, presumably accompanied by a separate preforming device, and then pulled through a heated stationary die where the resin polymerizes. The reinforcement is impregnated either by dragging it through a bath or by inserting the resin into an injection chamber that is usually attached to the die. Pultrusion can be done with a variety of resins, including polyester, polyurethane, vinylester and epoxy [61, 62].

2.3.4 Autoclave processing

An autoclave is a device that is used to perform industrial and experimental processes that require higher temperatures and pressures than the atmospheric pressure and temperature. In the chemical industry, autoclaves are used to cure coatings, vulcanize plastic and conduct hydrothermal synthesis, as well as in medical applications. Industrial autoclaves are used in a variety of industries, including the composites industry.

Autoclaves are often commonly used to cure composites, especially for melding multiple layers without voids that would weaken the material, and for vulcanizing rubber. Autoclaves produce high heat and friction, which helps to ensure that the best possible physical properties are repeatable. Autoclaves large enough to hold entire aeroplane fuselages made of layered composites are used by sailboat spar manufacturers, and some aerospace autoclaves are over 50 feet (15 m) long and 10 feet (3 m) high

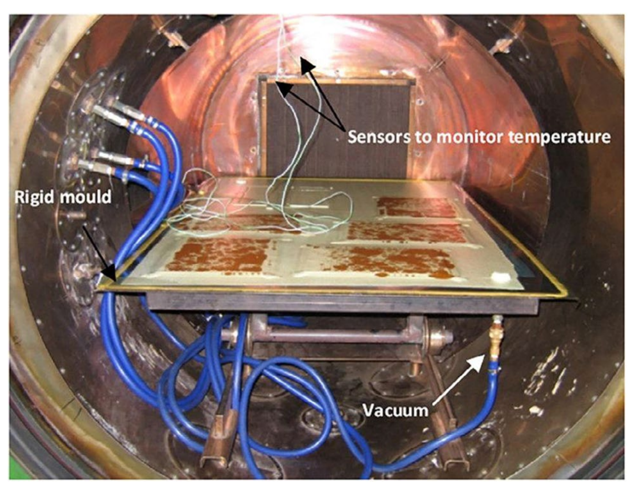


Fig. 11 Autoclave process [64]

[63, 64]. The standard autoclave curing of composites is seen in Fig. 11.

2.3.5 Hand layup processing

Hand layup is an open mould manual laminate composite preparation process that does not require the use of a power consuming unit. It is a normal ageing process in which the composites cure at room temperature and then need to be post-cured at a higher temperature for a period of time. This approach works well for thermosetting resins and woven roving pad fibre. It is a low-cost, low-waste and productive process since it requires the least amount of fuel. The mould material could be wood or any metallic material. Before casting the composites, the resin-fibre volume fraction should be determined on the basis of the strength required. Before making the composites, releasing agents such as wax or grease (oil) could be applied to the mould.

A liberal coat of resin should be added to the mould first, followed by a single layer of fibre woven mat spread over the resin coating and firmly pressed. This intervention means that the fibre mat is fully immersed in the resin and forms a bond. The remaining fibre mats could also be manually placed one by one. To ensure full resin and fibre bonding, a small amount of resin should be added between each fibre mat. A cotton roller or a metal paddle may be used to distribute the resin. The entrapped air bubbles should be carefully collected, since they can degrade the composites' longevity. Air bubbles in the resin may be easily removed with fin-type rollers. Curing could take up to 24 h. It can often be extended as a post treatment for up to 48 h [65, 66]. Figure 12 depicts a traditional hand layup method for composite construction.

3 Properties of aramid fibre-reinforced composites

3.1 Mechanical properties

Shankar et al. [67] studied the structural use of an aramid reinforced polymer matrix composite. The addition of aramid strengthened the mechanical properties of the base epoxy resin composite, according to the author. The increased mechanical properties are due to the aramid's high durability. Siliveo et al. [68] investigated the mechanical behaviour of epoxy composites reinforced with glass/aramid hybrid fabric and aramid plain fabric. In this study, the author used DGEBA epoxy resin to strengthen a hybrid form of glass and aramid fibre. The energy absorption behaviour improved as a result of the addition of aramid and e-glass fibre. Yahaya et al. [69] investigated the mechanical properties of woven kenaf-Aramid hybrid composites. In this study, woven hybrid composite was made in a laminate configuration using the hand lay-up process. Aramid/kenaf hybrid composites were made with a 30% overall fibre content and an aramid/kenaf weight fraction of 78/22, 60/40, 50/50, 26/74 and 32/68, respectively. The author concluded that hybrid composites with an aramid/kenaf (78/22) ratio had greater mechanical properties than other hybrid composites. The high strain-rate dynamic mechanical properties of aramid fabrics impregnated with shear thickening fluid were investigated by Saisai et al. [70]. A split Hopkinson pressure bar (SHPB) device was used to investigate the anti-impact mechanism, mechanical properties and energy absorption of the STF impregnated aramid (STF/Aramid) fabric at high strain rates. The energy transfer rate decreased from 0.85 to 0.01 as the number of fabric specimens increased from 2 to 8 layers, according to the author. Rashid et al. [71] evaluated

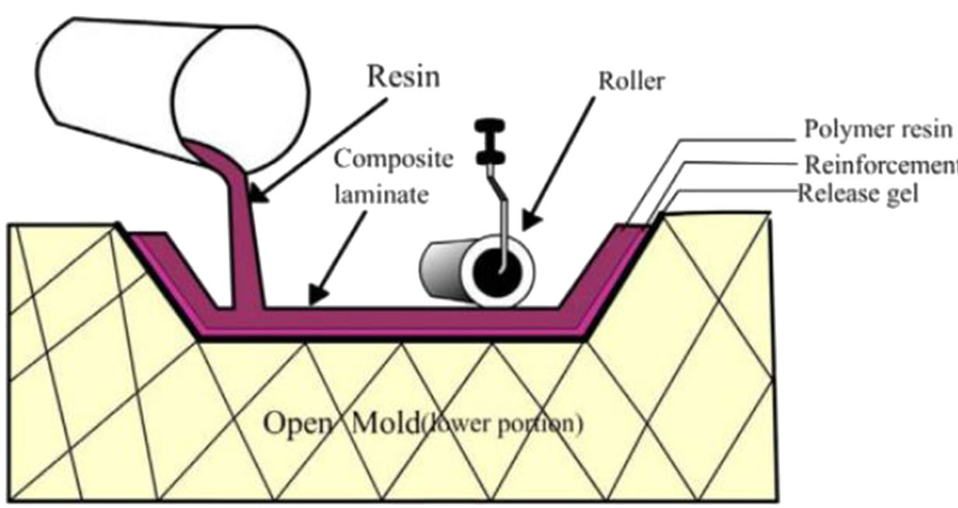


Fig. 12 Hand layup composite making technique (source: internet)

the mechanical properties of woven coir and aramid reinforced epoxy composites. The aim of this study is to assess the performance of hybrid textile reinforced epoxy composites in high-speed impact and flexural tests. Coir yarn, aramid yarn, interlaced coir and aramid yarn of separate warp/weft direction and pure epoxy as a control specimen were used to make the samples. Based on the findings, it was discovered that woven aramide composites samples have the best effect properties. Bresciani et al. [72] used macro-homogeneous and meso-heterogeneous methods to conduct experimental tests and computational modelling of ballistic impacts against aramid 29 plain-woven fabrics using an epoxy matrix. Aramid fibre in epoxy resin improved the damping coefficient and energy absorption efficiency, according to the authors. The mechanical behaviour of aramid/basalt reinforced polypropylene composites was studied by Aswani et al. [73]. Tension and in-plane compression testing revealed that composites containing a mixture of aramid and basalt yarns have greater tensile and compressive behaviour than their base composites. Zhu et al. [74] investigated the mechanical characteristics of Aramid 49 cloth when subjected to uniaxial, biaxial and in-plane wide shear deformation. The stress–strain response in the warp and fill directions, the apparent Poisson's ratio and the in-plane shear response of Aramid 49 fabric are investigated by the author, as well as the effects of specimen size and pre-loading on the fabric's mechanical responses. The fabric exhibits non-linear and orthogonal behaviour under strain, and can distort up to 20% before complete failure, according to the findings. Susmita et al. [75] conducted a study of aramid composites used in ballistic applications. According to the author, researchers discovered that incorporating aramid into the epoxy resin enhanced the composite's ballistic efficiency. Suthan et al. [76] conducted an experimental analysis to evaluate the mechanical properties of aramid fibre epoxy composites. The mechanical properties of a DGEBA-based epoxy composite with aramid fibre were investigated by the author. The ultimate tensile strength of the aramide reinforced epoxy resin composite is near 300 MPa, which is higher than that of aluminium, according to the author. For impact-resistant structures, Priyanka et al. [77] reviewed high-strength hybrid textile composites with carbon, aramid and e-glass fibres. The hybrid structures made with aramid, according to the author, produced better mechanical properties. Andrew et al. [78] used additive engineering to create continuous carbon, glass and aramid fibre-reinforced polymer composites. The study found that combining aramid with nylon improved tensile strength by 6.3 times over that of the non-reinforced nylon polymer. As a result, several studies and reviews concluded that adding aramid fibre to a polymeric medium increased the mechanical properties of composites.

3.2 Thermal properties

Chinnasamy et al. [79] investigated the thermal properties of glass and aramid fibres in modified epoxy hybrid composites. Fourteen layers of aramid were used to make the composites, both with and without nanoclay. According to the author, the thermogravimetry findings of composites revealed high thermal stability for nanoclay with aramid fibre. Ghouti et al. [80] developed multifunctional hybrid composites with improved mechanical and thermal properties based on polybenzoxazine and chopped aramid/carbon hybrid fibres. The composites with 20% aramid fibres and 20% carbon fibres had bending strengths and moduli of 237.35 MPa and 7.80GPa, respectively, according to the author. The same composites have had a tensile stress of 77 MPa and a toughness of 0.27 MPa, respectively. Using cyanate ester/benzoxazine resin and short aramid/glass hybrid fibres, Zegaoui et al. [81] developed high-performance polymer composites with improved mechanical and thermal properties. Compression moulding was used to effectively fabricate composites made of cyanate ester/benzoxazine resin blends reinforced with various proportions of silane-surface modified aramid and glass fibres. The thermal test results showed that increasing the volume of aramid fibre increased the thermal degradation stability significantly. Naveen et al. [82] investigated the thermal deterioration and viscoelastic properties of Aramid/Cocos nucifera sheath-reinforced epoxy hybrid composites. In this study, the weight ratios of Aramid and CNS were 100/0 (S1), 75/25 (S2), 50/50 (S3), 25/75 (S4) and 0/100 (S5). The findings of differential scanning calorimetry (DSC) showed that in epoxy composites, hybrid composite (S2) provides a virtuous resistance or stability to heat. Similarly, Mo et al. [83] investigated the use of an aramid/nano cellulose fibrils/softwood pulp hybrid to make composite insulating paper with low permittivity, strong mechanical and thermal properties. As replacements in the matrix, aramid pulp treated with low-temperature plasma and nano cellulose fibrils (NCFs) were used. The addition of 20% aramid pulp to the thermal results showed that the thermal degradation was increased, according to the author. Shiju et al. [84] investigated the physical and chemical interactions of graphene nano-composites with aramid-Nomex copolymer, as well as their thermal and mechanical properties. The inclusion of pristine graphene oxide and an aramid-Nomex copolymer increased thermal stability, according to the author. Thus, based on the limited literature, it has been determined that the presence or addition of aramid in the polymer matrix improves thermal properties.

3.3 Impact toughness properties

The impact resistance properties of aramid/glass fibre hybrid composite laminates were studied by Shaari et al. [85]. Vacuum bagging was used to create composite laminates with an epoxy matrix lined with twill Aramid woven fibre and clear glass woven fibre. Four different forms of composite laminates were created with different Aramid to glass fibre ratios (0:100, 20:80, 50:50 and 100:0). The results showed that combining Aramid and glass fibres increased the load carrying ability, energy absorption and damage degree of composite laminates while reducing deflection slightly. Bigdilou et al. [86] studied the impact properties of Aramid-ultrahigh molecular weight polyethylene fibres hybrid composites after incorporating carbon nanotubes. The result of inserting different percentages of carbon nanotubes (0.1, 0.3, 0.5 and 0.9 wt.%) and stacking sequenced aramid fibres and ultrahigh molecular weight polyethylene was explored in this research. When 0.1 weight percent carbon nanotubes were added to this configuration, the standardized absorbed energy increased by more than 6.5 times. Yang et al. [87] investigated the fracture and effect characterization of novel auxetic Aramid®/epoxy laminated composites. The Auxetic Aramid® composites showed a 225% increase in fracture toughness when compared to regular woven Aramid® composites, according to the author. The low velocity effect response of 2D and 3D Aramid/polypropylene composites was investigated by Bandaru et al. [88]. The surface treatment method enhanced the Aramid fabric's interfacial properties with the PP matrix. The fabric design has a significant effect on the low velocity impact reaction of Aramid/PP composites. As a result, the fabrics' in-plane stiffness improves their impact strength. Singh et al. [89] presented a research review of the characterization of aramid fibre and composites. According to the author, aramid fibre has become very common as reinforcement in composite materials due to its specific properties such as higher strength to mass ratio and modulus, and its use has grown significantly. Reis et al. [90] investigated the effect reaction of aramid composites with filled epoxy matrix in depth. The addition of fillers, according to the author, increases the maximum impact load and promotes lower displacements. The tensile and impact properties of Aramid, carbon and S-glass/epoxy composites reinforced with SiC particles were compared by Bulut et al. [91]. Aramid, carbon and glass fibre-reinforced composites with microscale silicon carbide (SiC) within an epoxy matrix were used to make the composites. The content of SiC particles and the fibre forms used as reinforcement are major parameters affecting composite tensile and impact resistance, according to the findings. Gokul dass et al. [92] investigated the mechanical and low-velocity effect behaviour of an intra-ply glass/aramid fibre-reinforced nano-silica and micro-rubber transformed epoxy resin hybrid composite. Glass/aramid-49 intra-ply woven fabric, micro rubber and nanoclay were used to make the hybrid composites. The composites of micro-rubber and nano-silica modified epoxy resin reinforced with 50 wt% intra-ply glass/Aramid fibre had overall tensile/flexural strength and modulus of 223/131 MPa and 9.73/6.2 GPa, respectively, according to the author. Hu et al. [93] investigated low-velocity impact damage on CFRPs with aramid-fibre toughening. With short Aramid-fibre toughening, the compression-after-impact (CAI) strengths and failure strain values increased at all energy levels, according to the author. As a result, there is more evidence for adding aramid fibre to improve low velocity impact toughness, which is obvious when any real-time application requires high damping and energy absorption requirements.

3.4 Time-dependent properties

Hashim et al. [94] looked into the impact of fibre loading directions on low cycle fatigue in intraply carbon-aramid reinforced epoxy hybrid composites. The fatigue linear regression lines showed a slower degradation rate in the aramid loading direction than in the carbon loading direction, according to the author. Yin et al. [95] investigated the reinforcing effect of aramid fibres on the fatigue activity of SBR/aramid fibre composites. Under the stress-control condition, the author prepared a composite with aramid and SBR material and recorded a standardised progress in fatigue life in the composite, which was approximately 4 times. Alsaadi et al. [96] explored the impact of nanosilica incorporation on the complex mechanical activity of fibre-reinforced carbon/aramid hybrid composites with epoxy resin. The addition of nanosilica particles to aramid improved the damping and dynamic mechanical behaviour, according to the author. The behaviour and mechanism of fatigue crack growth in aramid-fibre-reinforced styrene–butadiene rubber composites are studied by Yin et al. [97]. According to the source, aramid fibres (AF) in styrene–butadiene rubber (SBR) packed with carbon black (CB) show enhanced fatigue behaviour as fatigue strain changes. Tan et al. [98] investigated the dynamic mechanical activity of an impact polypropylene copolymer reinforced with long aramid fibres. The findings of the dynamic mechanical nature of long aramid fibres reinforced IPC composites show that with the inclusion of aramid fibres, the composite deformation resistance and glass transition temperature improved significantly. The value of the surface modification process on the properties of aramid/epoxy composites was explained by Ramasamy et al. [99]. According to their findings, chemically treating the Aramid surface raises the polar functional groups and strengthens the interfacial adhesion between the fibre and the epoxy. The tensile fatigue and flexural moduli of treated aramid fibres were increased by up to 38% as compared to untreated aramid fibres, according to the source. Zhong et al. [100] improved the fatigue properties of styrene butadiene rubber composites by enhancing the interface adhesion between coated aramid fibres and matrix. The role of coated aramid fibre fabric in dynamic loading was verified in this research, and evidence of progress was established. Nashat et al. [101] investigated the static and dynamic mechanical properties of short Aramid fibre-reinforced composites manufactured using direct ink writing. The addition of aramid fibre to the epoxy resin enhanced the static and dynamic loading behaviour, according to the research. For dental-post applications, Fouad et al. [102] investigated the crack hardness, vibration modal analysis and viscoelastic behaviour of aramid, glass and carbon fibre/epoxy composites. According to the author, vibration modal analysis revealed that the frequency response of the carbon fibre composite was lower than that of glass and Aramid composites. The mode-I fracture hardness of carbon fibre/epoxy composites interleaved by aramid nonwoven veils was investigated by Beylergil et al. [103]. The propagation Mode-I fracture durability values of CF/EP composites can be greatly improved (by around 72%) using aramid nonwoven fabrics, according to the authors. Sharma et al. [104] found that multiscale bucky paper interleaved Aramid fibre composites had better static and dynamic mechanical properties. The addition of multiscale bucky paper to the aramid epoxy resin composite improved dynamic loading behaviour by 31%, according to the authors. Overall, the study of different researchers shows that the incorporation of aramid fibre to polymer composite technology plays an important role due to its intrinsic toughness and low thermal expansion coefficient.

3.5 Machining of aramid composites

Sri et al. [105] have done a review study on machining of aramid fibre composites. They confirmed that the machining aramdi fibre composites are more stable at low temperature than elevated temperatures. Gill et al. [106] studied the mechanisms of high rates of tool wear in the machining of aramid honeycomb composites. The results of the tool wear test showed a standard tool wear timeline. The collapse of honeycomb cells was reported by the twisting far in advance of the arrival of the tool, according to author. Vigneshwaran et al. [107] have reviewed the abrasive water jet machining of fibre-reinforced composite materials. Author concluded that the abrasive water jet machining (AWJM) was proven to be more effective and a preferable technique in machining of aramid fibre-reinforced composite material, according to the discussion. Rajesh et al. [108] have done a research study on the optimization of machining parameters of aramid natural hybrid composite in abrasive water jet machining using Taguchi method. Author confirmed that the abrasive flow rate is more responsible for producing high MRR with lower surface roughness in composite. Rangaswamy et al. [109] studied the machining of kevlar aramid fibre-reinforced polymer composite laminates (K-1226) using solid carbide step drill K34. Author concludes that the solid carbide step drill K-34 material was better option to drill high thickness kevlar reinforced composite. lei et al. [110] have done a performance analysis of drilling test of aramid fibre composite. As the verdict, the tool geometry has a great influence on the drilling performance of AFRP. Due to poor drilling quality, 8-face drill and twist drill are not suitable for drilling AFRP drilling tools. The machining quality of Brad & Spur drill is relatively good, which can meet the drilling requirements of AFRP. Similarly, Liu et al. [111] have done a comprehensive investigation of cutting mechanisms and hole quality in dry drilling woven aramid fibre–reinforced plastic with typical tools. According to the investigation, laminate interfacial adhesion is the main cause for producing high dimensionally stable machined drills. Thus, based on the literatures, machining of aramid fibre-reinforced polymer composites are easy as other commercial fibre-reinforced plastics and there is no different kinds of other machining methods are required.

3.6 Industrial applications of aramid-based composites

3.6.1 Aircraft

The use of aramid ® 49 in aircraft components was investigated by Khusiafan et al. [112]. According to the author, kevlar ® 49 is an outstanding material for reinforcement in aircraft components. It is strong in tensile, light in weight, inert in certain environments, stiff and robust. Centred on stress analysis, Mohammed et al. [113] evaluated composite material used in the wings of a modern aeroplane. This author concentrated on the study of raw materials used in new aeroplane wings. Fibreglass, carbon fibre or aramid-based composites like aramid are examples of these materials. The maximum tensile strength of graphite-epoxy is 2.9 times that of fibre glass and 5.5 times that of Aramid-epoxy, according to the findings. Furthermore, the findings of bending stress tests indicate that aramid-epoxy has a 30% higher maximum strength than glass fibre and a 75% higher maximum strength than graphite-epoxy. The standard aircraft wing model studied in this analysis is shown in Fig. 13.

3.6.2 Automobile

A systematic analysis of hybrid composites for automotive applications was published by Ravishankar et al. [114]. The use of aramid fibre in car parts was highlighted in this study. The high toughness of aramid, according to the author, has led to widespread use of this fibre in the automotive industry.

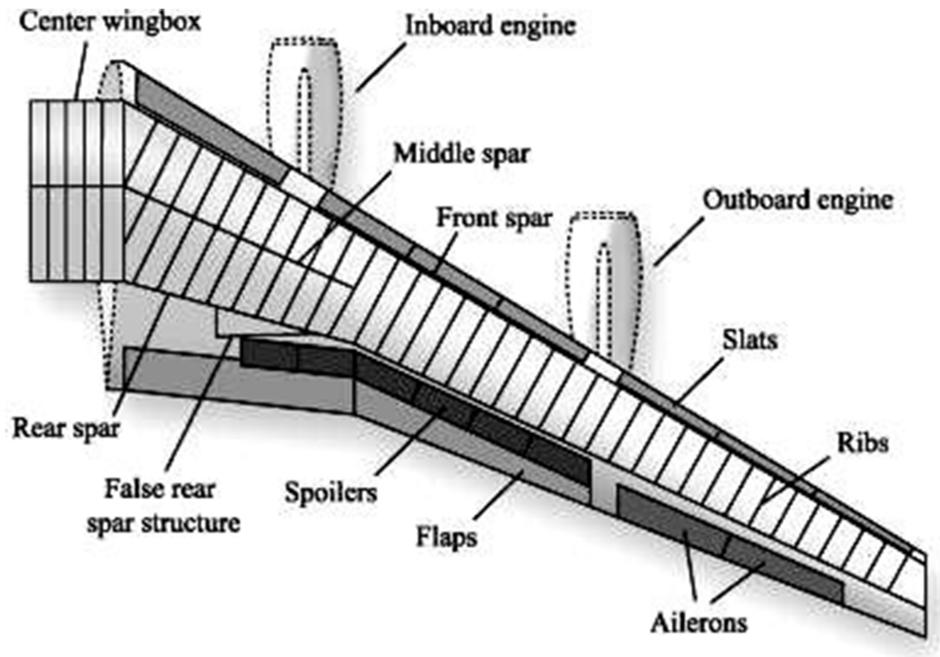


Fig. 13 Aircraft wing model [113]

Hovorun et al. [115] used a variety of resources to research modern materials for the automotive industry. Polyurethanes, polyvinylchlorides, polypropylenes, ABS plastics and fibreglass plastics make up about 80% of the plastics used in automobiles, according to the author. Polyethylenes, polyamides, polyacrylates and polycarbonates make up the remaining 20%. Every fibrous filler that is impregnated with silicone resins is referred to as fibre glass. Carbon fibre, glass fibre and aramid are the most well-known fillers. The bodies' exterior panels are made of fibre glass, resulting in a substantial reduction of the car's mass. Figure 14 depicts vehicle components that can withstand high-performance new-generation materials like aramid-based composites.

Patel et al. [116] examined lightweight composite materials for use in automotive manufacturing. According to the author, since the rise in environmental concerns, the weight-saving requirement for automobiles has become more important. Lightweight composite materials are critical for improving fuel economy, as well as ensuring the safety and efficiency of new cars. Since it takes less energy to accelerate a lighter object than it does to accelerate a heavy one, lightweight composite materials have a lot of potential for improving automotive performance. Author noted that lightweight composite materials such as Mg and Al metal matrix composite, biomass, glass and aramid fibre-reinforced polymer composites can directly reduce the weight of automotive parts by replacing steel, and cast iron traditional components with lightweight composite materials such as Mg and Al metal matrix composite, carbon, glass and aramide fibre-reinforced polymer composites can directly reduce the weight of automotive parts by replacing steel and cast iron traditional components with lightweight composite materials such as Mg and Al metal matrix composite, Rajak et al. [117] looked at how aramid-based composites could be used in automobiles. Hybridising aramid fibres (KFs) with glass or carbon fibres improve the thermal properties of Aramid fibre-reinforced composites (KFRCs), though there is less research on hybridising aramid fibres (KFs) with natural fibres. KFRCs have high impact strength and tensile properties, but they have low compression strength compared to glass and carbon fibre counterparts due to their anisotropic nature, according to the author. Ramar et al. [118] have done a study on design and analysis of composite leaf spring using aramid fibre. Author revealed that the aramid fibre is a suitable material for high damping applications such as leaf spring and other shock load absorbers. Similarly, Liu et al. [119] have done research study on fabrication and investigation of aramid fibre-reinforced airship envelops materials for various engineering application. Author confirmed that the high tensile strength of kevlar based composites is good in load bearing capabilities. Kwon et al. [120] have investigation of impact resistance performance of carbon fibre-reinforced polypropylene composites with different lamination to applicate fender parts. According to the study, the carbon and aramid fibre-reinforced epoxy resin composites are good in impact resistance properties.

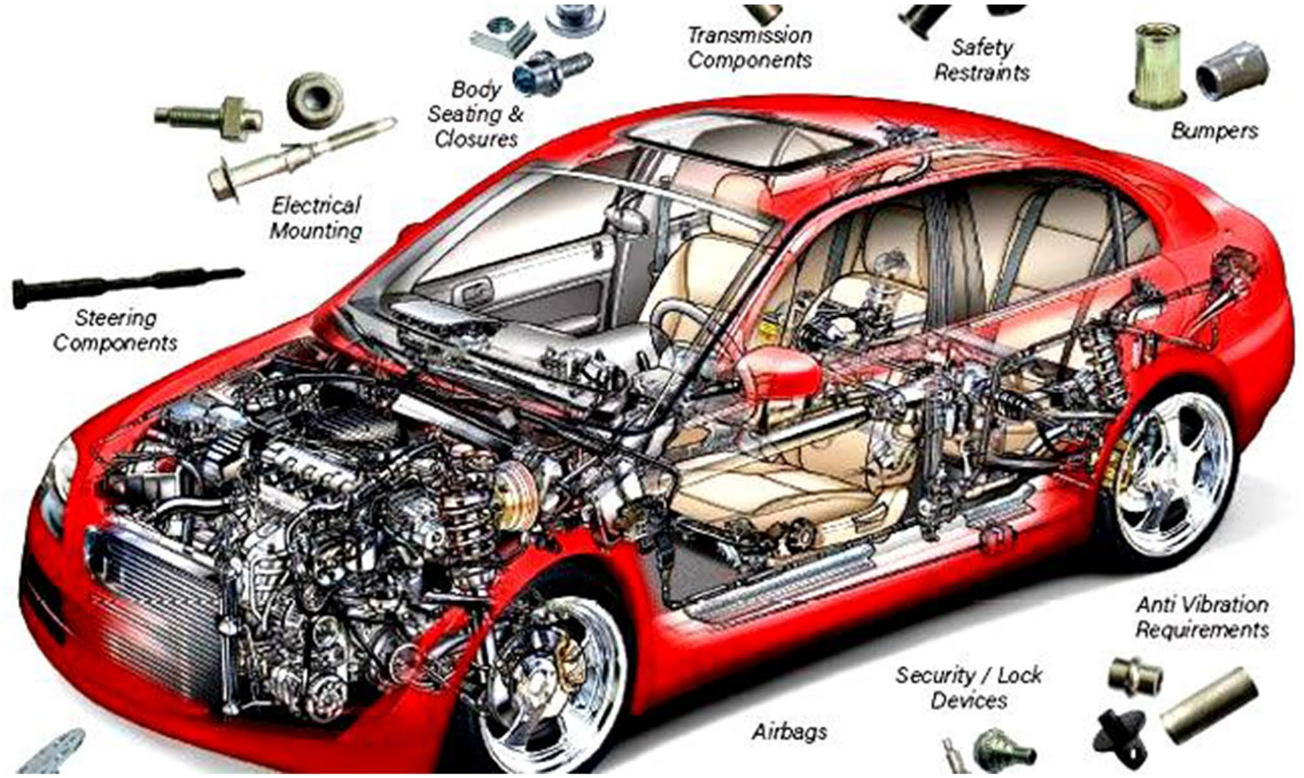


Fig. 14 The various parts of automobile equipped with composite material

3.6.3 Energy

Mutkule et al. [121] discussed the optimum and reliable material for wind turbine blade. The blade of turbine plays important role. Wind turbine blade performance is determined by the form, height, strength and density of the blade material. The material used to improve the performance of wind turbine blades is extremely important. Turbine blade materials should have the above-mentioned main properties, such as low density, high strength and long fatigue life. Material should also be designed to withstand high aerodynamic inertia, fatigue load and environmental effects such as dust particle aggregation and moisture ingredients. To improve efficiency, the author suggests that aramid-based composite blades could be a good replacement for high inertia steel blades. The effect of fibre orientation on the behaviour of composite materials in horizontal axis wind turbine blades was discussed by Rajad et al. [122] (HAWTB). The effects of different fibre orientations in the epoxy matrix were discussed by the author. As the verdict, the fibre orientation 45°/45° produced improved mechanical and fatigue properties in wind turbine blade. Mishnaevsky et al. [123] looked at the different types of materials used in wind turbine blades. The importance of aramid fibre in the polymer matrix medium was highlighted by the author. They suggested that aramid, which has a high hardness, could be used in prime mover applications. Similarly, Kalagi et al. [124] investigated the use of natural fibres in the production of wind turbine blades. The treated fibre may have a high resistance to laminar shear failure under shear stress, according to the author. Overall, glass, aramid and natural fibres are the latest trend composite for high-energy-efficiency prime mover applications.

4 Conclusions

The fibre weaving, processing, treating methods and composite making routes for aramid fibre-reinforced polymer matrix composite materials are successfully reviewed in this review. The role of aramid fibre and its application in various engineering domains also revealed with suitable examples. According to the summary of this review work, it is clear that the aramid is a potential fibre for various engineering applications especially light weight high toughness applications. It has high damping effect, which facilitate this fibre could be the suitable candidate for many engineering applications. However, the surface modification of aramid found to be producing better results on machining behaviour compared to as-received fibre. Thus, over all, the aramid (kevlar) fibre could be spelled out as a potential fibre for many new trend engineering applications.

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