Engineering Materials

ENGR 220

KEVLAR

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Abstract

Kevlar is one of the most emerging materials of the moment, and which, in turn, enjoy a versatile utility in different industrial and production fields. Kevlar has a unique combination of high strength, high modulus, toughness and thermal stability. It was developed for demanding industrial and advanced-technology applications. This paper is based on a detailed summary of this aramid fiber, analyzing each of its applications, highlighting which are its most essential uses for today's world and justifying the special peculiarity of the composition of its fibers. This document also comprehensively and precisely covers the exposition of the material's properties, both physical and mechanical, clarifying and introducing information such as its Young's modulus value, the elongation capacity of its fibers, and even the manufacturing and development process of this polymer.

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Introduction

As a technical description, Kevlar, an organic fiber in the aromatic polyamide (aramid) family combines high strength with light weight, and comfort with protection. Much of its success is due to the versatility and properties it contains.

When we talk about Kevlar, we talk about progress and evolution, we talk about present and future, and we talk about advancement multiplied which means that the advancement from Kevlar leads to new progress in technology and creating a new thread of progressions. This new aramid fiber has the power to generate a domino effect of new inventions from the prior and revolutionize the STEM industry as we know it. Kevlar is that type of material that allows us to grow technologically and allows and will allow thousands of new fibers and materials to be developed due to its great use capacity.

It has a wide range of destinations for its use, and always plays an essential and irreplaceable component role.

As a way to familiarize yourself with the material, Kevlar is frequently compared to, the basic and elemental material, steel. As it has been mentioned previously, this polyamide has high resistance and hardness, which is 5 times greater than that of steel on an equal weight basis and provides reliable performance and solid strength, as well as being very tough and having little electrical conductivity.

Motivation

The motivation I have to be interested in Kevlar and go more deeply into its details and characteristics is due to the exploration and interest that has arisen in the composition of different materials and objects that are useful and fundamental to us in everyday life.

When looking for information on the most emerging materials of the moment, and which, in turn, enjoy a versatile utility in different industrial and production fields, I have come across Kevlar.

It is a material that, although it encompasses numerous applications of lesser importance, we can also find it used for multiple purposes, such as the design of sports equipment, protective clothing for construction workers, improving body armor, such as bullet proof vests and military armor/equipment.

Kevlar, in short, is that type of material that can be used for any type of field, and that you can find both in tennis shoes and as a vital piece in the production of the newest and latest generation aircraft.

Applications

One of the most common uses of Kevlar and for which more recognition and information is had about it, is for its application in personal protective equipment (PPE) such as bulletproof vests or military weapons because it is an excellent material at providing protection from bullets and knife jabs, thanks to their high tensile strength, which allows it to absorb great amounts of energy before giving way.
Even so, Kevlar is also used in the composition of such common and everyday objects such as tires, music and sports equipment, motor vehicles, among others.

- **Body armor**

Body armor made with Kevlar reduces the chance of bodily injury or death caused by physical, ballistic, stab, and slash attacks. It provides an excellent performance, superior strength, and extreme flexibility.

One of the reasons for the success this material has in PPE military and corps weaponry is that, due to Kevlar's molecular structure and great tensile strength, it is capable of stopping a bullet.

- **Automotive and motor vehicles**

This para-aramid synthetic fiber does the function of achieving an Increasing performance in automotive components. Due, once again, to the solid structure of the inter chain bonds.
The material brings together temperature resistance, strength, reinforcement and other properties that can help improve filters, belts, gaskets and other automotive components.

Modern racing cars also contain Kevlar-reinforced fuel tanks. The high tensile strength of Kevlar makes the fuel tanks inherently difficult to puncture in this case of an accident.

- **Sports equipment:**

Kevlar is used in both snowboards and skis for their core material. The combination of being both lightweight, as well as incredibly strong makes the chances of your board or skis breaking on a crash significantly less likely. It also allows for more tension and leeway when carving the slopes.[2]

Another way Kevlar is used is for the inner lining of bicycle tires. Not only does this help prevent holes in your tires, but it also increases the lifespan so your tires will last longer. [2]

Sport clothing companies are also starting to make shoes applying this organic fiber in the sole, insoles, coating.

- **Cables**

In the fine gauge cable industry, Kevlar provides excellent robustness, fatigue tolerance, shrinkage resistance, and reliability to consumers.

This DuPont brand aramid fiber has provided a lightweight, flexible, and dimensionally stable means of helping to strengthen ropes and cables used across several industries, from mountaineering ropes and fishing lines to electro-mechanical cables and fine gauge cables for electronic device applications such as mobile phone cables, computer power cords, USB cords, and MP3 earphone cables.

The fiber's resistance to chemicals and temperature extremes makes it an excellent part for ropes and cables that must withstand heavy loads in rugged conditions, from the ocean's depths to Mars' surface.

1. Definition

Kevlar is a heat-resistant para-aramid synthetic fiber with a molecular structure of many inter chain bonds that make Kevlar incredibly strong. Best known for its use in ballistic body armor, Kevlar also has many other applications because of its high tensile strength-to-weight ratio. [1]

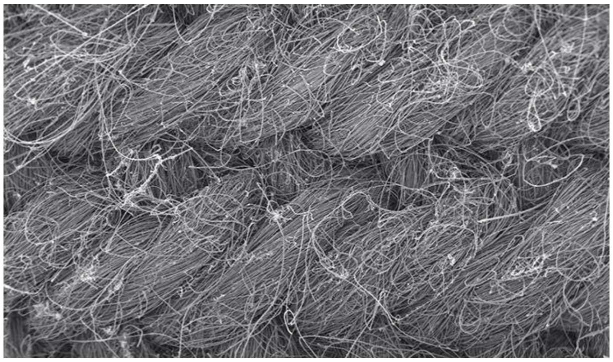

Figure 1. Kevlar inter-chain bonds [1]

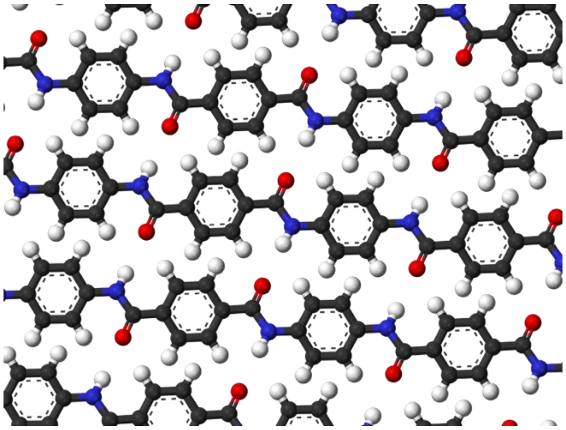

Figure 2. Ball-and-stick model of a single layer of the crystal structure [2]

Kevlar was invented by chemist Stephanie Kwolek in 1965 while working at DuPont. The research reason for the inclusion of a new material and compound was the foreseeable gasoline shortage that loomed in 1964. [2]

She began to work with her team to find an alternative to the composition of the tires of the moment, since, at that time, despite their unquestionable durability, they were too heavy and tiring for the engine.
The research was based on discovering a new ultra-light and strong fiber to use on tires. The goal was to provide the same properties the tires already had, just modifying the weight to make them lighter.

The polymers she had been working with at the time, poly-p-phenylene terephthalate and polybenzimidazole, formed liquid crystal while in solution, something unique to those polymers at the time. [3]

As she has recounted numerous times, "the solution was cloudy, opalescent when shaken, low in viscosity, and was generally thrown away. “I persuaded the technician, Charles Smullen, who was running the row, to try the solution, and I was surprised to find out. that the fiber did not break, unlike nylon. The supervisor and the laboratory director understood the importance of my discovery and a new field of polymer chemistry quickly emerged" [4].

After its discovery and being put into use, it was time to develop and exploit this new synthetic fiber to the fullest.

Kevlar began serving as a basis for the production and discovery of many other new Aramids, including Flame-Resistant Meta-Aramid material called Nomex.
With this, Kevlar took the function of core research and experiments to, based on its powerful and novel composition, create new variants. Currently, many types of Kevlar are produced to meet a broad range of end uses.

- **Kevlar K-29 –** It is a high toughness grade used in industrial applications, such as cables, body/vehicle armor, brake linings.
- **Kevlar K49 –** It has a high modulus used in rope and cable products.
- **K100 –** The colored version of Kevlar
- **Kevlar K119 –** It has higher-elongation, and more fatigue resistant
- **Kevlar K129 –** It is a higher tenacity grade utilized in ballistic applications
- **Kevlar AP –** It has 15% higher tensile strength than K-29

1.1 The Class of Materials

Kevlar is DuPont’s name for aramid fibers. Aramid fibers are light weight, strong, and tough. The main types are Kevlar 49, which has a high stiffness, and Kevlar 29, which has a low stiffness. An advantage of aramid fibers is their high resistance to impact damage, as a result making them often used in areas prone to impact.

Aramid fibers' biggest drawback is their overall vulnerability in compression and hygroscope. According to service records, some Kevlar sections can consume as much as 8% of their weight in water. As a result, pieces made of aramid fibers must be shielded from the elements.
Another downside is that drilling and cutting Kevlar is challenging. The fibers fuzz easily, and special scissors are needed to cut the material. Kevlar is often used for military ballistic and body armor applications. It has a natural yellow color and is available as dry fabric and prepreg material. Bundles of aramid fibers are not sized by the number of fibers like carbon or fiberglass but by weight [1].

At its core Kevlar is an extremely lightweight, yet strong synthetic polymer that is weaved into a material that is 5 times stronger than steel when the weight is equal. Kevlar has an incredibly high tensile strength that is 8 times stronger than steel wire [1].
Kevlar can be used by itself or as part of a composite material (one material combined with others) to give added strength.

1.2 The Structure of Atoms

1.2.1. The electrons in an Atom

To explain electrons and their occupation and location in the atom, I am going to use the similarity that water and Kevlar have in this regard. In both compounds, the oxygen atoms have a high electron density around the nucleus. Since electrons are negatively charged, oxygen atoms will have a slight negative charge.

On the other hand, hydrogen atoms have a much lower electron density around the nucleus, thus having a partial positive charge. Hydrogen and oxygen in various molecules attract each other, forming the hydrogen bond [9].

1.2.2. The electronic structure of the solid: energy bands and chemical bonds

Kevlar is known as an aramid fibre. It is a polymer. A polymer is a substance which has a molecular structure built up of a large number of similar units, called a monomer, bonded together to form a long chain.

Kevlar is made by a condensation reaction of an amine (para-phenylene diamine) and acid chloride (terephthaloyl chloride, PPD-T chloride). The resultant aromatic polyamide contains aromatic and amide groups which makes them rigid rod like polymers, and it is more properly known as a para-aramid. The aramid ring gives Kevlar thermal stability. The para-structure makes it strong and increases the modulus [5].

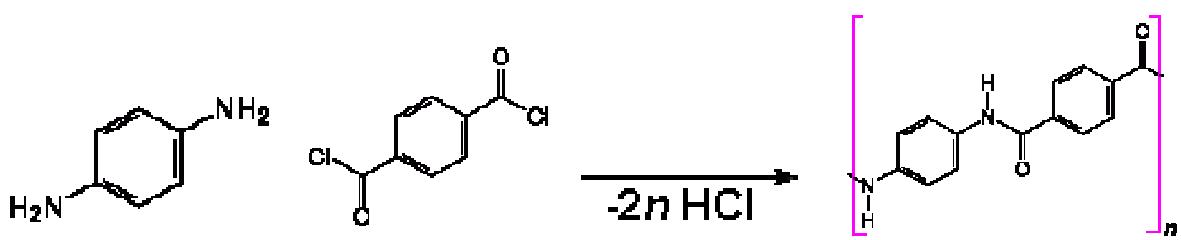

Figure 3. Condensation reaction and formation of para-amarid. [5]

Kevlar fibre is an array of molecules orientated parallel to each other. It looks like a pack of uncooked spaghetti. The orderly, untangled arrangement of molecules is described as the crystalline structure.

The crystallinity is obtained by the spinning manufacturing process. This process involves the extrusion of molten polymer solution through small holes [5].

The composition is anisotropic, meaning that the fiber is stronger in the longitudinal direction than in the axial direction. The fiber composition of the extruded material causes it to have weak shear and compression properties. Between the polar amide groups and neighboring chains, hydrogen bonds form. Specific Kevlar polymer chains are held together by hydrogen bonds.

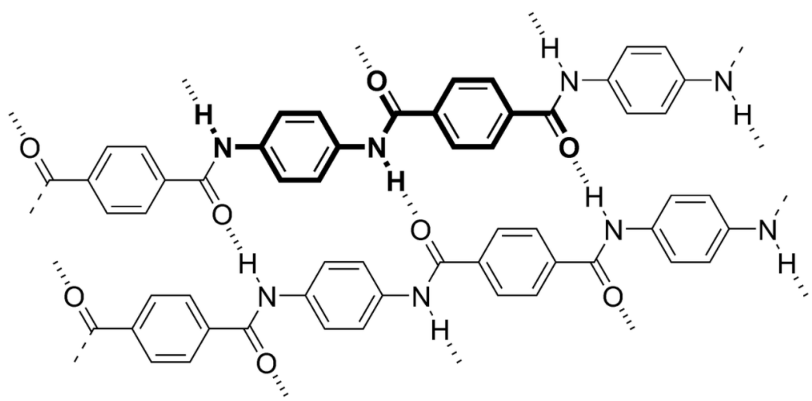

Figure 4. Individual Kevlar chain [5].

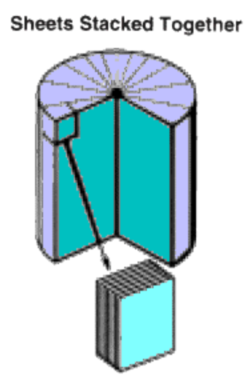

Figure 5. Rod-Like Fiber Structure by the Radial Stacking of Hydrogen-Bonded Sheets [9]

1.2.2. The electronic structure of the solid: energy bands and chemical bonds

The supramolecular organization of the aromatic polyamide fiber Kevlar 49 has been studied using a combination of electron diffraction and electron microscope dark-field image techniques. The dark-field images derived using selected reflections from longitudinal sections exhibit axial banding of two main types having periodicities of 500 and 250 nm. Careful analysis, including tilting experiments, conclusively shows that the supramolecular architecture of these fibers consists of a system of sheets regularly pleated along their long axes and arranged radially [6].

This paper develops a complex multiscale model based on Kevlar structures from the molecular scale to the macroscopic scale in order to provide a better understanding of the mechanical deformation of the material. The high modulus of Kevlar fibers can be due to the high stiffness of aromatic polyamide chains and the massively spaced hydrogen bonds in the material, according to the molecular structures of Kevlar.

At the microfibril size, injury initiation and evolution in Kevlar fiber can be observed.
It can be found that the material strength in the grain boundary regions is only 1.9 GPa, resulting in much lower strength of the whole Kevlar fiber (2.5–3.3 GPa), compared to the theoretical strength of the aromatic polyamide crystals (>30 GPa) [4].

The contribution of Kevlar fiber structural parameters (pleated distance, misorientation angle, and skin thickness) to the stretching action of a Kevlar Bundle is also investigated, which is essential for the future improvement of aromatic polyamide fibers for reinforcement purposes in advanced equipment.

2.Physical Properties

Kevlar is a revolutionary material in terms of composition and utility. The great ability to be applied to countless fields has been the trigger for its great success in recent decades. All this is due to the exceptional and unique properties of fiber; Kevlar's physical properties are a combination of high levels of toughness, tenacity, dimensional stability, accompanied in turn by properties such as low ductility, low coefficient of thermal expansion, low electrical conductivity, among others.

In general, it is a material that possesses structural rigidity, due to its high modulus of rigidity, and it has a high chemical resistance, which allows it the excellent performance as one of the best aramid fibers known to date.

2.1 Density

The density of a substance is its degree of compactness, which is calculated by dividing the mass of the material by the volume. As we know, Kevlar standard density of Kevlar 29 and Kevlar 49 fibers share the same density value: 1440 kg/m^3. Another density that I want to mention is the density of the modification Kevlar 149, which is bit higher 1470 kg/m^{3}m, helps to form the highly crystalline fibers of this modification, used as reinforcing dispersed phase composite aircraft components [13].

A study to take in account is the following one, where the effect of hybridization of fabrics on wear properties of epoxy composites, including Kevlar, is shown. With this aim seven types of composite were prepared. These are only carbon, glass, Kevlar fabric reinforced composites and carbon/glass, carbon/Kevlar, glass/Kevlar, carbon/glass/Kevlar hybrid fabric reinforced composites.

The effect of fabric content on the density of the composites is given in Figure 6. As expected, the presence of glass fabric has caused a considerable increase in the density of composites. Glass has the highest density among these three fabrics [8].

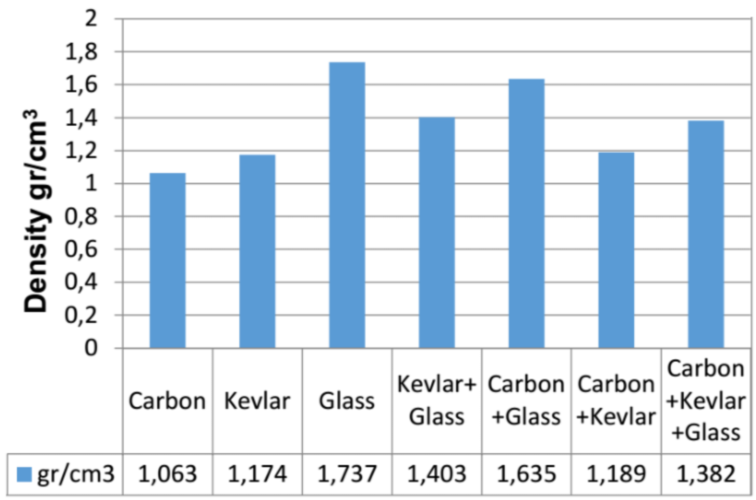

Figure 6. Density of composite specimens

2.2 Thermal conductivity

Kevlar (polyparaphenylene terephthalamide) is known as a lightweight and strong synthetic fiber with high tensile strength and Young's modulus. The thermal conductivity of a Kevlar 49 has been measured in the 7–290 K temperature range.
From these calculations and from some other studies, it is known that, with a maximum error of 4%, the thermal conductivity is of 4.0 W/(mK) at a temperature of 290 K (23 $^{\circ}$C).

Kevlar is an aramid fiber that enjoys great thermal stability thanks to the complex and solid composition of the chemical and molecular structure of the polymer.
Kevlar is inherently flame resistant — protecting against thermal hazards up to 800 degrees Fahrenheit. Additionally, the fibers will never melt, drip or support combustion [1].

2.3 Electrical conductivity

The electrical conductivity, represented by the Greek letter σ, is very low, therefore, we can call Kevlar as insulator of electricity.

The ability of this material or substance to let the electric current pass through it is very low. Because conductivity depends on the atomic and molecular structure of the material, the structure of the Kevlar is characterized because it has many united electrons between them. Through very strong links, they impede the movement between the atoms, disabling the fluidity of any type of electrical current. The conductivity, in turn, also depends on other physical factors of the material itself.

The electrical resistivity, commonly represented by the Greek letter ρ, is the reciprocal of electrical conductivity. The specific electrical resistance of a material quantifies how strongly it resists electric current. It is described through the following equations:

$$\rho = \kappa \times R = R\frac{A}{\ell}$$

The electrical resistivity is measured by the ratio between the crossed sectional area (A) and the length of the material (ℓ), multiplying the theorical resistance of the material (R).

The direct relationship between the conductivity and resistivity is the following formula:

$$\sigma = \frac{1}{\rho}$$

In our case for Kevlar, the strength to resist electric current is 1015 Ω · m.

So, this high resistivity rate explains some of the uses that are given to Kevlar. We can see this fiber in guy lines in transmission towers, helmets and safety bulletproof clothing and tires resistant to punctures.
Although it is not conductive, it can absorb water and the water does conduct electricity (or rather minerals in the water make it conductive.) so in such applications a waterproof coating is applied to the Kevlar [10].

2.4 Superconductivity

Superconductivity, in its definition, is a set of physical properties observed in certain materials where electrical resistance vanishes and magnetic flux fields are expelled from the material. Any material exhibiting these properties is a superconductor [11]. This basically means that they would not lose absolutely no energy in any form as they are transferred.

There are two types of superconductors type which I which is constructed of basic conductive elements but under extreme pressure to reach the superconductive state [12]. Then there are type II superconductors which are composed of a metallic compound such as copper or lead and they reach their superconductive state at extremely elevated temperatures [12].

As I have mentioned previously, Kevlar is an insulator of electricity, therefore, in turn, it is impossible for it to be called a super conductor because it does not conduct electricity without losing energy as it undergoes resistance.

2.5 Specific heat

The specific heat is the ratio of the quantity of heat required to raise the temperature of a body one degree to that required to raise the temperature of an equal mass of water one degree. [14] On the following table, the specific heat of the two most significant variants of Kevlar measured by following the conditions of the metric system at different temperatures is shown:

Property	Unit	Kevlar® 29	Kevlar® 49
Specific Heat			
At 77°F (25°C)	cal/g x °C (J/kg x K)	0.34 (1,420)	0.34 (1,420)
At 212°F (100°C)	cal/g x °C (J/kg x K)	0.48 (2,010)	0.48 (2,010)
At 356°F (180°C)	cal/g x °C (J/kg x K)	0.60 (2,515)	0.60 (2,515)

Table 1. Table of the different specific heat values of Kevlar.

As exhibited in the previous table, the specific heat of Kevlar is markedly influenced by temperature. It more than doubles when the temperature is raised from 32°F (0°C) to 392°F (200°C), as seen in Figure 7.2. Further increases are more gradual.

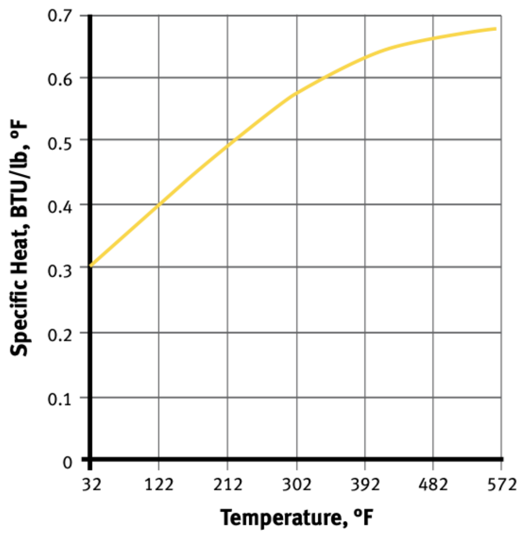

Figure 7.1. Effect of Temperature on the Specific Heat of Kevlar® 49.

On the following figure, it can be observed the measure of the specific heat of a variety of materials over a range of different temperatures. Taken from the report, it is said that "the measured values are close to, but do not perfectly match the literature provided by the material manufacturers".

As we can see, this time graphically and in the form of a comparison with other types of materials such as cork or alumina mat, Kevlar shows its property of increasing the specific heat as the temperature is being increased, showing a gradual growth as the temperature becomes higher and higher [20].

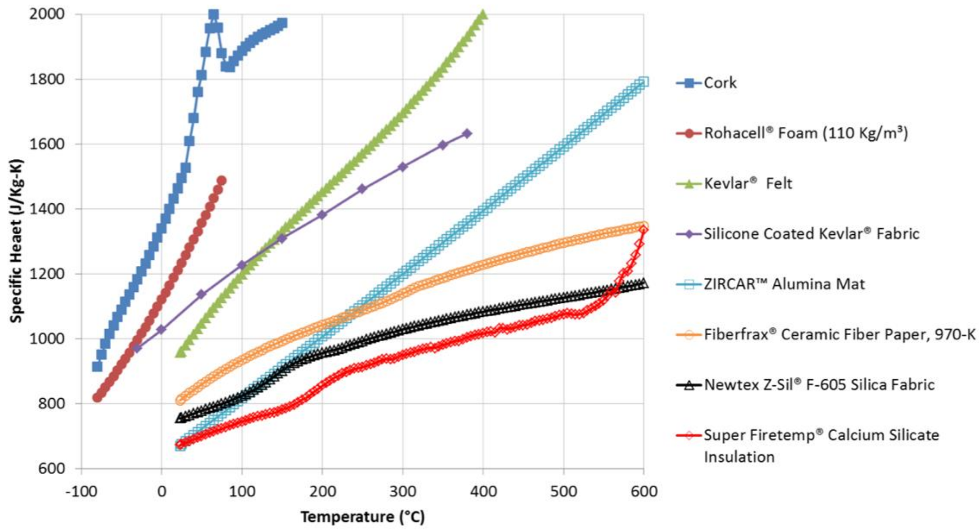

Figure 7.2. Measured values of specific heat as a function of temperature.

2.6 Melting range

The melting range between the corrected temperature at which the substance begins to collapse or form droplets on the wall of a transparent glass capillary tube and the corrected temperature at which it is completely melted as shown by the disappearance of the solid phase [15].

Kevlar® does not melt; it decomposes at relatively high temperatures (800°F to 900°F [427°C to 482°C] in air and approximately 1,000°F [538°C] in nitrogen), when tested with a temperature rise of 10°C/minute. Decomposition temperatures vary with the rate of temperature rise and the length of exposure.

	Decomposition Temperature, °F	Decomposition Temperature, °C
Kevlar® 29	800–900	427–482
Kevlar® 49	800–900	427–482

Table 2.1, Decomposition temperature of Kevlar.

The effect of subjecting Kevlar at such high temperatures is directly reflected in the dimensional stability of the fibers that make up the material.

The polymer, even so, would not shrink under any circumstances as other types of organic fibers do when they are exposed to hot water or hot air. These organic fibers are capable of undergoing significant changes in their structure, even becoming irreversible after shrinkage.

2.7 Thermal expansion

Kevlar’s coefficient of thermal expansion is 4µmK. Thus, the tendency of Kevlar to change its shape, area, volume, and density in response to a change in temperature has very small and negative coefficient, which results in low internal stress in differential temperatures. [17]

This coefficient of thermal expansion describes how the size of an object changes with a change in temperature. Specifically, it measures the fractional change in size per degree change in temperature at a constant pressure, such that lower coefficients describe lower propensity for change in size. The value of the CTE of Kevlar is dependent on measuring technique, sample preparation and test method [8].

Type of Kevlar®	Denier	Temperature Range °F	°C	CTE in./in./°F (cm/cm/°C)
Kevlar® 29	1,500	77–302	25–150	-2.2 x 10^{x} (-4.0 x 10^{x})
Kevlar® 49	1,420	77–302	25–150	-2.7 x 10^{x} (-4.9 x 10^{x})

*Tested with zero twist and 0.2 gpd tension at 72°F (22°C), 65% relative humidity (RH).

Table 2.2. Coefficient of Thermal Expansion (CTE) of Kevlar 29 and Kevlar 49

Enlargement of dimensions is indeed the commonly expected effect of heating on most materials. Kevlar fibres behave differently: they manifest a negative axial CTE and a positive coefficient in the transverse plane. Negative axial CTE though not very common is not unique to Kevlar. PE, carbon, PBO, hinged polydiacetylene and some composites are examples of plymers which exhibit a negative axial thermal expansion.

In the case of Kevlar, this negative axial coefficient of thermal expansion is closely associated with its structural characteristics. Molecules of PPTA of which Kevlar is made include inherently planar phenyl groups and amide segments. [18]

Despite the extensive use of Kevlar fibres in structural engineering, studies on the estimation of its CTE have not been many. Anisotropy in the thermal expansion behaviour of Kevlar 49 fibres was first reported by DuPont Inc., which commercially introduced these fibres. Later, Strife andPrewo17 measured the CTE of uni- and bi-directionally rein-forced Kevlar composites, using dilatometry. In both the cases, the thermal expansion of the composite was shown to be anisotropic. [18]

2.7.1 Thermal Behavior

Kevlar maintains its strength and resilience down to cryogenic temperatures (−196 °C); in fact, it is slightly stronger at low temperatures. At higher temperatures the tensile strength is immediately reduced by about 10–20%, and after some hours the strength progressively reduces further. For example: enduring 160 °C (320 °F) for 500 hours, its strength is reduced by about 10%; and enduring 260 °C (500 °F) for 70 hours, its strength is reduced by about 50%. [3]

Kevlar, as carbon fiber does, becomes very resistant to exposure to elevated temperatures. Neither have a melting point. Both Materials have been used for protective clothing and fabrics used near fire. Kevlar are used to make protective firefighting or welding blankets or clothing. Kevlar gloves are commonly used in the meat industry, to protect hands while using a knife [10].

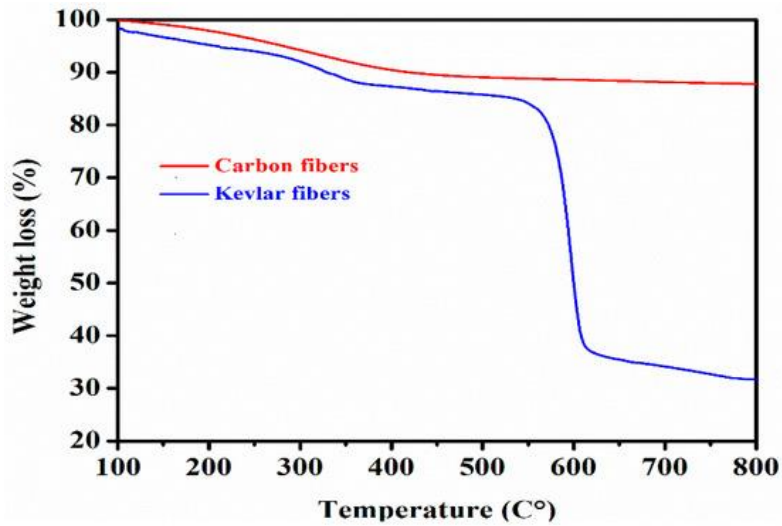

Figure 8. Thermal stability of the carbon fibers and Kevlar fibers.

Furthermore, to explain the thermal enhancement of the hybrid composites, I wanted to display a study based on hybrid fibers consisting of chopped Kevlar and carbon fibers, which were subjected to a silane surface treatment, being incorporated into the resin matrix in various combinations, and then isothermally cured using the compression molding technique. [19]

This thermal stability analysis of Carbon fibers and Kevlar fibers was also carried out to obtain a clear indication about their roles in providing excellent thermal properties of the hybrid composites.
As reported in Figure 10, the CFs showed good thermal stability when compared to the Kevlar fiber properties, this could be related to the microstructural properties of CFs, which, as their name indicates, mainly contain carbon, and the presence of graphite in their structure is known for its high thermal resistance. Effectively, the weight losses at 5% and 10% were at 280 °C and 418 °C, respectively, with no major weight loss up to 800 °C for the CFs. However, the weight loss of the KFs at 5% and 10% were 190° C and 313 °C, respectively, with the char yield of 31%% at 800 °C. [19]

We can conclude that the main factor enhancing the thermal stability was the CFs, with less influence from the KFs. [19]

2.8 Optical properties

Kevlar fibers have a characteristic yellow color that is very identifiable with the material itself. Kevlar has this yellow color in most of the different applications it has, therefore, this material is very identifiable and unmistakable with other types of synthetic fibers.

Optical properties are also identified as the interactions of a specific material when this is exposed to light. If the fibers of this material are able to absorb the light, then, this is known as refraction capacity, and if, instead, they reflect the light coming onto, it is known as reflection. This is all measured by the solar reflectance index (SRI) [22].
Light colored materials usually have a higher solar solar reflectance value than darker materials as more light can be reflected back into the atmosphere but generally the SRI value an opaque material is between 0, which means no solar energy is reflected, and 1, which means all solar energy is reflected [22].

The high birefringence of Kevlar results in a high order white retardation color so the natural color of the fiber dominates. Small staple fibers can be seen roughly paralleling the horizontal fiber in this image. These small staple fibers are often associated with Kevlar fibers. One of the fibers in this image shows the node-like pattern seen in some Kevlar fibers [21].

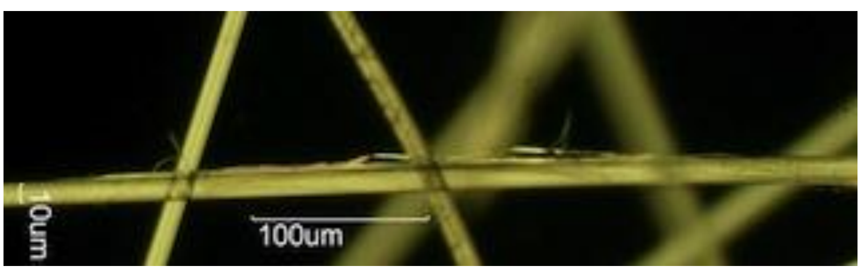

Figure 9.1. Node-like pattern of Kevlar fibers.

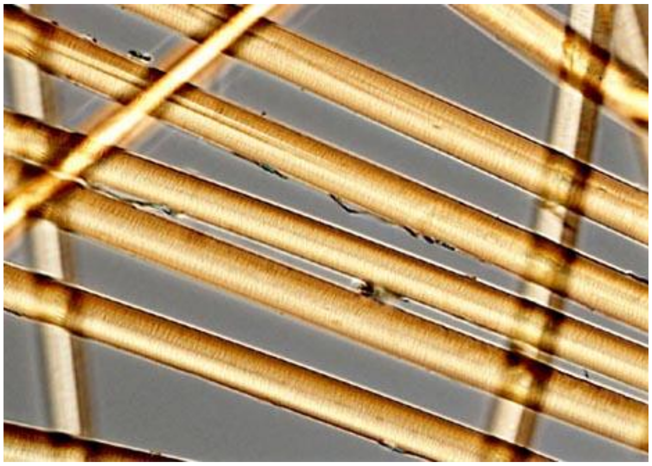

Figure 9.2. Kevlar fiber under the microscope.

Kevlar is yellow and can have the highest birefringence, 0.685, and parallel refractive index, 2.322, of any of the synthetic fibers. Typical values for the refractive indices of Kevlar (29 and 49) are 1.646 perpendicular and 2.05 parallel, which gives a birefringence of about 0.4, still the highest by far of any of the synthetic fibers. The different types of Kevlar can sometimes be differentiated by the banding that occurs along the length of the fiber [21].

Figure 9.3. Piece of Kevlar suitable for use.

2.9 Corrosion resistance

Corrosion resistance refers to the resistance a material offers against a reaction with adverse elements that can corrode the material [23].
The process of corrosion is observed when an object is oxidized by environmental contaminants, resulting in the loss of electrons. Corrosion resistance refers to a metal's ability to retain its binding energy and endure the oxidation and chemical breakdown that would otherwise occur in such an environment [23].

Kevlar has a great with resistance toward any type of corrosion, thus are galvanic, stress-corrosion cracking, pitting, among many others. Kevlar is also really resistant to heat, that is why this fiber is used in vast applications such as aerospace engineering (such as the body of the aircraft), bulletproof vests, car brakes, and boats, or some applications specialized in many different types of body armor.

2.10 Phase transformations

When the composition or structure of a substance varies, we call it phase transformation A change of temperature may induce the transition without involving any other materials, or it may require a reaction with another substance, which may or may not be a ceramic and may be in the liquid or gaseous phase [24].

In the case of Kevlar, and so, many other crystalline polymers, they exhibit phase transitions between the low- and high-temperature phases during the heating process. Sometimes, however, the temperature-dependent measurement of the X-ray diffraction peaks, and vibrational spectra leads us to the incorrect conclusion that these two phases transform in a direct solid-to-solid transition mode instead of the melt and recrystallization process [25].

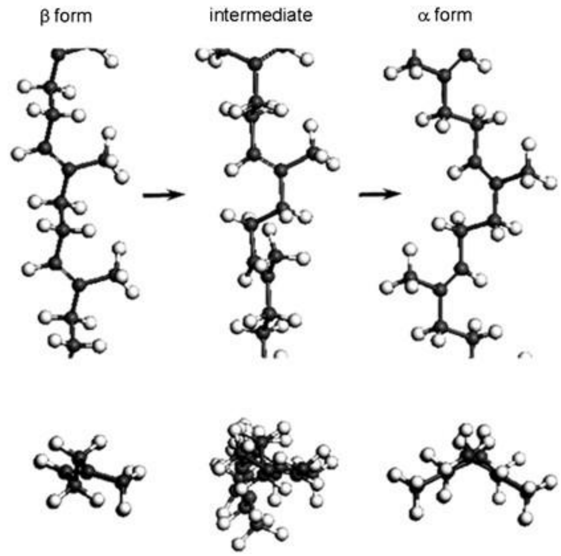

Figure 10. Schematic illustration of the structural transformation from the β-form to the α-form via the intermediate liquid-crystalline phase.

3. Mechanical Properties

When we talk about mechanical properties, we refer to those physical properties that a material exhibits upon the application of forces [26].

The list of all the mechanical properties that a material can have is quite long. Within it, there are particularities that are of greater interest and importance, and there are others that remain more in the background when describing the material.

In this paper, we will primarily focus on properties that are useful and attractive for fields such as the technology and engineering fields. With this, we will obtain a better cognition of the Kevlar material and, as a consequence, a better understanding of the qualities and benefits Kevlar provides and how much it differentiates it from other materials that are already so well established in the world of science.

As it has been mentioned before, when it comes to mechanical properties, Kevlar is one of the materials best endowed with these characteristics.

Kevlar consists of relatively rigid molecules, which form a planar sheet-like structure similar to silk protein. These properties result in its high mechanical strength and its remarkable heat resistance.

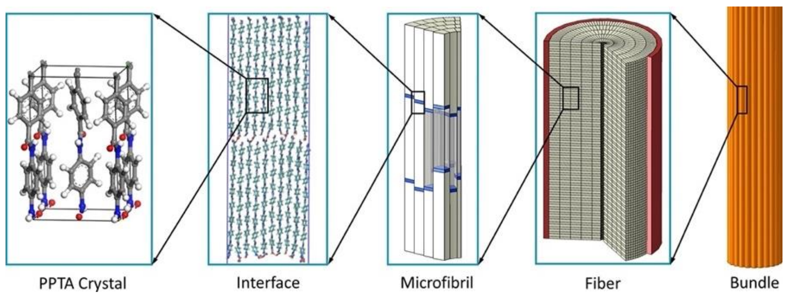

Figure 11. Multiscale model of Kevlar fiber for mechanical properties evaluation.

As we can see in Figure 16, Kevlar is manufactured as a fiber and woven into sheets. To obtain an insightful understanding of the mechanical construction of Kevlar, a detailed multiscale model is developed in this paper based on the structures of Kevlar from molecular scale to macroscopic scale. By analyzing the molecular structures of Kevlar, the high modulus of Kevlar fibers can be attributed to the high stiffness of aromatic polyamide chains and the massively distributed hydrogen bonds in the material. The high modulus, low cost, impact resistance, and flexible nature make Kevlar an ideal material for an inflatable design.

3.1 Yield strength

The most commonly used value in engineering calculations is yield stress or yield power. It determines how much stress a material can withstand in MPa before deforming plastically. The yield point is the name for this region. Previously, after raising a load, a substance will return to its original shape. The deformation is irreversible after it exceeds the yield limit.

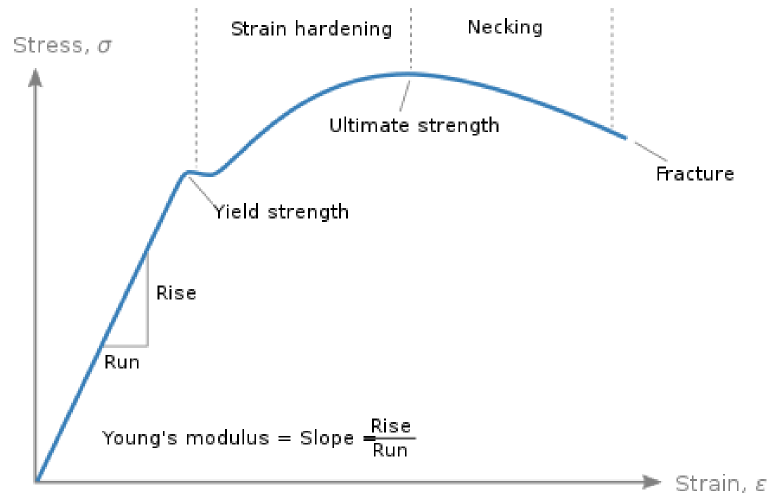

Figure 12.1. Generic stress-strain curve.

In the following image it can be seen the evident difference in slope, technically known as Youngs modulus, of the 3 different Kevlar variants. The graph, however, does not display the material's deformation at all.

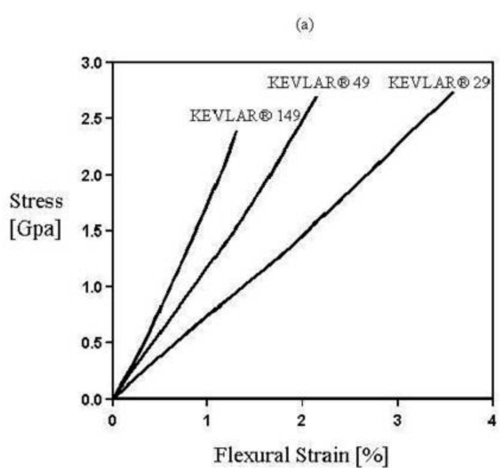

Figure 12.2. Yield strength curve of Kevlar fibres [28]

Kevlar possesses a higher yield strength per density than most alloys, such as titanium and aluminum. This yield strength per density for Kevlar (898.5 Mpa*m3/kg) is approximately eight times greater than the yield strength per density of titanium (187.5 Mpa*m3/kg) or aluminum

(98.6 Mpa*m3/kg). This difference results in significant mass and volume savings for Kevlar over other materials.

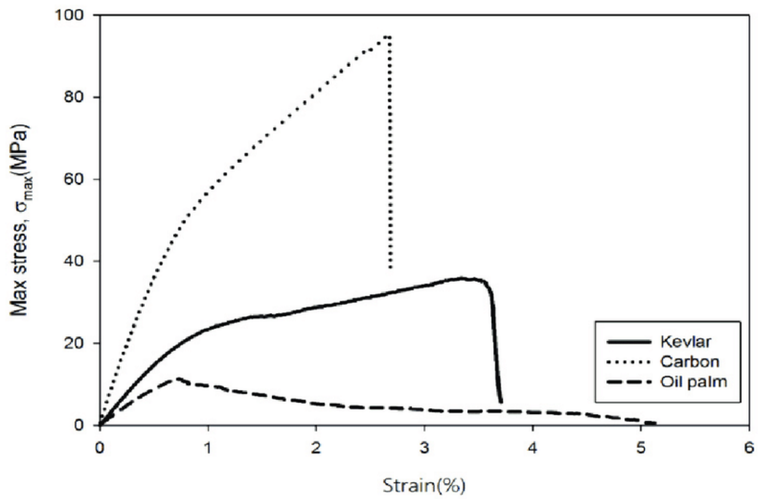

Figure 12.3. Tensile stress-strain curve of Kevlar and carbon hybrid with oil palm EFB/epoxy composites [28]

Figure 17.2. shows the stress-strain curve of tensile properties for Kevlar/oil palm EFB/Kevlar, carbon/oil palm EFB/carbon and oil palm EFB/epoxy hybrid composites. The function of tensile-strain curve is to show the mechanical behavior of the materials. It is shown how all the three composites develop a linear increase in the tensile stress [28].

However, only carbon/oil palm EFB/carbon and Kevlar/oil palm EFB/Kevlar hybrid composites showed a drastic decrease in the curve.

From the results, Kevlar/oil palm EFB/Kevlar hybrid composites is seen to have an intermediate, but still, high tensile strength which is 36.1 MPa as compared to EFB/carbon oil palm/epoxy composites [28].

3.2 Tensile strength

The tensile strength of a material is the maximum amount of tensile stress that it can take before failure, for example breaking.

When talking about Kevlar, we know that we are talking about a polymer that is tough and very hard to break. Kevlar has a tensile strength of about 3,620 MPa, and a relative density of 1.44 g/cm^3. The polymer owes its high strength to the many inter-chain bonds. These inter-molecular hydrogen bonds form between the carbonyl groups and NH centers. Additional strength is derived from aromatic stacking interactions between adjacent strands. These interactions have a greater influence on Kevlar than the van der Waals interactions and chain length that typically influence the properties of other synthetic polymers and fibers [3].

Grade	Density g/cm^3	Tensile Modulus GPa	Tensile Strength GPa	Tensile Elongation %
29 (High Toughness)	1.44	83	3.6	4.0
49 (High Modulus)	1.44	131	3.6-4.1	2.8
149 (Ultrahigh Modulus)	1.47	179	3.4	2.0

Table 3.1. Comparison table for Kevlar variants and their respective tensile values.

As can be seen from the previous table, depending on the different grades of Kevlar, tensile modulus varies greatly.

Even though the density remains at the same common value (1.44-1.47 g/cm^3), the value of the tensile modulus changes even up to 50 units. This is due to the fact that, as the Kevlar grade increases, the fibers that make up the material are more tenacious, making it more difficult to elongate and stretch the material, becoming more prone to fracture.

	Specific Density, lb/in.^{3}	Tenacity, 10^3 psi	Modulus, 10^6 psi	Break Elongation, %	Specific Tensile Strength,* 10^6 in.
Kevlar® 29	0.052	424	10.2	3.6	8.15
Kevlar® 49	0.052	435	16.3	2.4	8.37
Other Yarns					
S-Glass	0.090	665	12.4	5.4	7.40
E-Glass	0.092	500	10.5	4.8	5.43
Steel Wire	0.280	285	29	2.0	1.0
Nylon 66	0.042	143	0.8	18.3	3.40
Polyester	0.050	168	2.0	14.5	3.36
HS Polyethylene	0.035	375	17	3.5	10.7
High-Tenacity Carbon	0.065	450	32	1.4	6.93

Table 3.2. Comparative Properties of Dupont™ Kevlar® vs. Other Yarns.

**Specific tensile strength is obtained by dividing the tenacity by the density.*

3.2.1 Elastic and Plastic Deformation

Measurement of deformation history during a high-speed mechanical test plays an important role in establishing the dynamic behavior of materials. Traditional strain measuring techniques such as extensometers and strain gauges have limitations such as frequency response and range of strain. Kevlar 49 fabrics were tested in tension within a strain-rate range of 25 to 170s−1
170 s^{-1} using a high-speed servohydraulic testing system [30].

Results show that the dynamic material properties in terms of Young’s modulus, tensile strength, maximum strain, and toughness increase with increasing strain rate. The woven nature of Kevlar 49 fabric results in large displacements and shape changes during tests. Non-contacting strain measuring technique is therefore highly preferred [30].

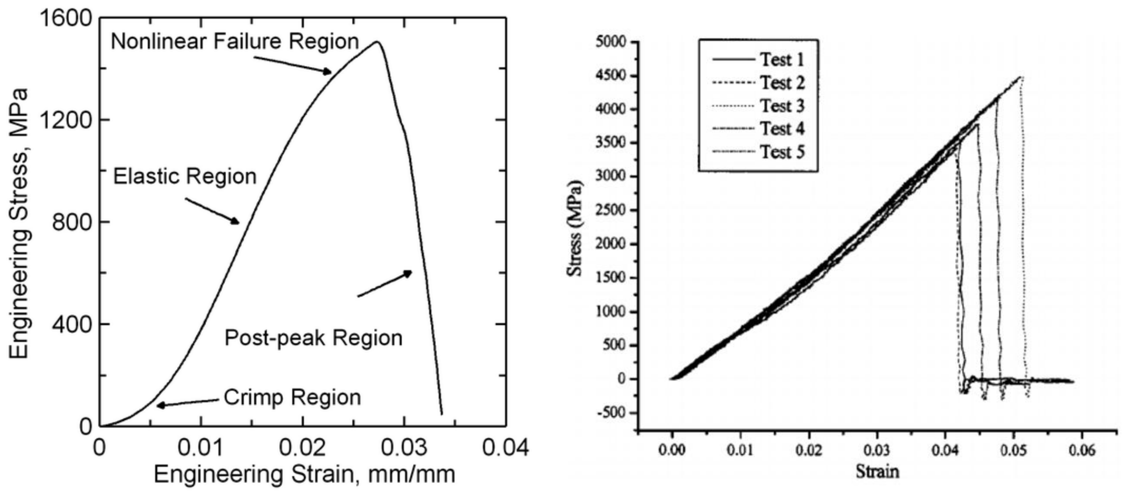

Figure 13.1. Kevlar strain-stress graph of 5 different tests [29], [30].

As it is compared in the following graph, Figure 19.2., when it comes to the comparison of Kevlar with other materials, this organic fibre always performs in a very remarkable and optimal way. Kevlar's failure point, where the fracture is reached, is very far from the x-axis compared to the rest of the materials shown in the graph. The fibers are endowed with the ability to withstand very high levels of strain with respect to stress, suffering forces that instigate breakage, but achieving this to be prolonged up to 3.6%.

This shows quantitatively how the stiffness of Kevlar increases and the elasticity of its mechanical response increases as the fibrillar microstructure becomes more oriented along the tensile axis.

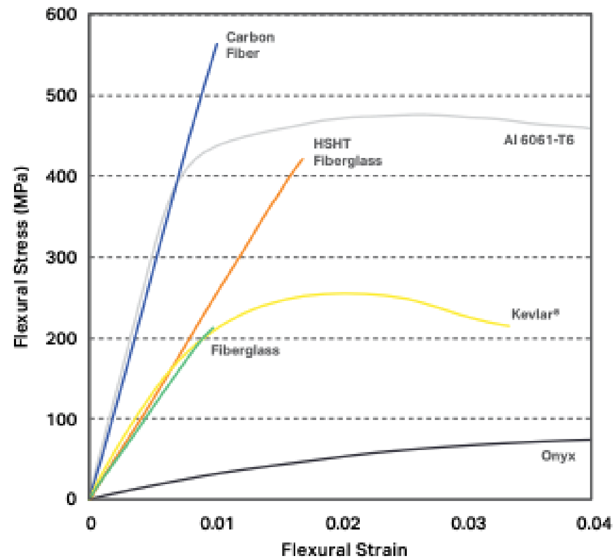

Figure 13.2 Comparison of the flexural stress-strain curves of different materials.

3.3 Shear strength

The strength of a material, in general, is the value by which yielding, fracture or excessive deformation occurs in a load-carrying member. Shear strength is a material property that describes a material's resistance against a shear load before the component fails in shear. The shear action or sliding failure described by shear strength occurs parallel to the direction of the force acting on a plane [31].

Shear strength and shear stress are often used interchangeably, but there is a technical distinction between the two. Shear stress is relative, and it changes in relation to the amount of shear load applied to a material per unit area. On the other hand, shear strength is a fixed and definite value in the general nature of a material [31].

However, Kevlar lacks inquiry into this mechanical property, so there is not a specific value to give with respect to the shear strength of Kevlar.

There are still some studies online about the in-plane shear strength of hybrid aramid/epoxy composites that allow us to get a slight knowledge about the potential shear strength of Kevlar and its performance in the engineering field.

On the basis of the obtained results as summarized in the following table, the addition of modified aluminosilicates significantly improved the behavior of the composite during tension at an angle of 45 degrees. In addition, an upward trend was observed as the clay content increased. As in the case of tensile and bending, higher values of the in-plane shear strength and in-plane shear modulus were obtained for the composites containing bentonite modified with quaternary ammonium salt [32].

Material	Shear Strength at 5% Shear Strain, MPa	Shear Displacement at 5% Shear Strain, mm	Shear Modulus, MPa	Max Shear Strength, MPa	Max Shear Displacement, mm
EP/Kevlar	18.3 ± 1.0	3.53	474.7 ± 24.0	23.3 ± 1.1	12.5 ± 2.1
EP+1%BAQAS/Kevlar	20.6 ± 0.9	4.10	609.1 ± 26.6	30.7 ± 4.4	23.1 ± 2.4
EP+3%BAQAS/Kevlar	22.8 ± 0.8	4.18	674.0 ± 27.1	34.7 ± 3.1	25.9 ± 2.6
EP+1%BAQPS/Kevlar	20.2 ± 1.2	4.13	591.0 ± 19.6	28.1 ± 2.1	19.5 ± 2.3
EP+3%BAQPS/Kevlar	21.9 ± 0.6	4.23	677.0 ± 17.3	29.4 ± 3.3	17.4 ± 3.5

Table 4. Tensile properties of Kevlar reinforced composites [32].

3.4 Elongation

Elongation is a measure of deformation that occurs before a material eventually breaks when subjected to a tensile load. As the latter is applied, an increase in length and a uniform reduction in cross-sectional area take place, while the material maintains a constant volume [34].

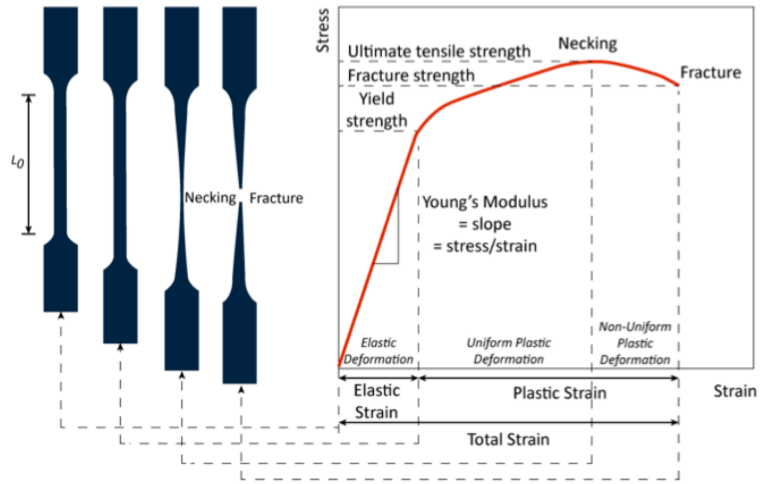

Figure 14. Graphic representation of elongation

The formula for elongation at any length L during tensile testing is:

- δ = elongation, (in or mm)
- L_0 = initial gauge length between marks, (in or mm)
- L = length between marks at any point during uniform elongation, (in or mm)

$$\delta = \mathrm{L} - L_0$$

The rate of elongation of a loaded Kevlar-49 fiber is measured as a function of time at 4.2 K. The result puts a worst-case upper limit of 0.028% in the elongation rate ΔL/L for a 0.5 mm diameter fiber kept under a constant tension of 2.7 kg for 8 months. A value that is probably closer to reality is actually 0.004%. This result proves that Kevlar-49 can be safely used in cryogenic applications in which high mechanical stability under stress is required [33].

	Specific density (lb/in^3)	Tenacity, 10^3 (psi)	Modulus, 10^6 (psi)	Break Elongation (%)
Kevlar 29	0.052	424	10.2	3.6
Kevlar 49	0.052	435	16.3	2.4
Steel Wire	0.280	285	29	2.0
Nylon 66	0.042	143	0.8	18.3
Polyester	0.050	168	2.0	14.5

Table 5. Specific break elongation and some other properties put to comparison.

As it is shown in the table and previously it could have been seen in other different comparisons in the form of graphs and tables, Kevlar 29 and Kevlar 49 have a determined break elongation percentage: 3.6% and 2.4%, respectively. It is concluded that, compared to materials such as steel wire or high-tenacity carbon, it has a higher percentage of break elongation. However, Kevlar does not stand out, far from it, for being a material capable of withstanding tensile load to a high degree. But, on the contrary, it is considered a considerable low elongation at rupture.

3.5 Young's modulus

The Young's Modulus of a material is a fundamental property of every material that cannot be changed. It is a value that is dependent upon temperature and pressure, however.
Known as well as the modulus of elasticity in tension, E, it is a mechanical property that measures the tensile stiffness of a solid material. It quantifies the relationship between tensile stress, σ, (force per unit area) and axial strain, ε, (proportional deformation) in the linear elastic region of a material and is determined using the formula:

$$E = \frac{\varepsilon}{\sigma}$$

Young's Modulus is in essence the stiffness of a material. In other words, it is how easily it is bended or stretched, and it is measured in gigapascals (GPa).

Kevlar has a Young's modulus of 76 GPa, a value within the expected standards, due to its remarkable ability to withstand stress without breaking but, at the same time, without having a very significant elongation capacity.

3.6 Modulus of rigidity

The modulus of rigidity, G, or shear modulus is the coefficient of elasticity for a shearing force. Specifically, it is defined as "the ratio of shear stress to the displacement per unit sample length" The modulus of rigidity can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material [36].

$$G = \frac{F * l}{A * \Delta x}$$

Where:

F = the force which acts

A = area on which the force acts.

Δx = transverse displacement

L = initial length of the area.

The measure of the rigidity of the body, given by the ratio of shear stress to shear strain, of Kevlar is 19 GPa. It is a fairly standard figure and intermediate among other values, which allows Kevlar to be rigid enough to be able to adopt and fulfill functions related to toughness and resistance, but at the same time, it is not restricted from exercising many other functions related to elasticity and forces producing deformation [36].

3.7 Ductility

The ability of a material to be drawn or plastically deformed without fracture is known as ductility. It is therefore an indication of how 'soft' or malleable the material is.

We can measure the ductility of a material having the original gauge length, L_0 , and a final gauge length, L_F , after necking and fracture. The ratio of the difference in the final length and original length to the original length itself is known as percent elongation (%δ), or, in other words, the capability to turn out into a wire [34].

The formula that represents this measurement is:

$\% \delta$ = percent elongation, (%)

L_F = final specimen length, (in or mm)

L_0 = original specimen length, (in or mm)

$$\%\delta = \frac{L_F - L_0}{L_0}$$

The ability of Kevlar to have its shape changed without losing any type of strength or breaking is pretty good. Taking in consideration many studies and research of Kevlar and its ability to be ductile, it can be said that Kevlar is endowed with high ductility.

Moreover, a specific study has come to the following conclusion: “Improved ductility was obtained for polymerisation filled composites, as a result of better fibre-polymer interfacial adhesion, whilst ductility decreased upon increasing fibre content and strain rate. Several models for short fibre composites are compared in their prediction of tensile strength for these composites, to include the effect of critical fibre aspect ratio” [37].

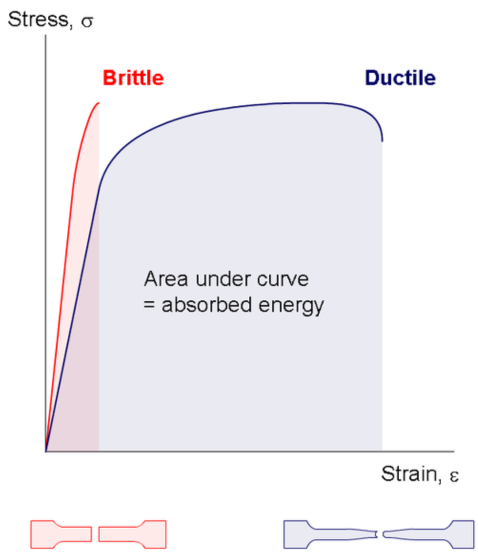

Figure 15.1. Brittle vs. ductile stress-strain behaviour.

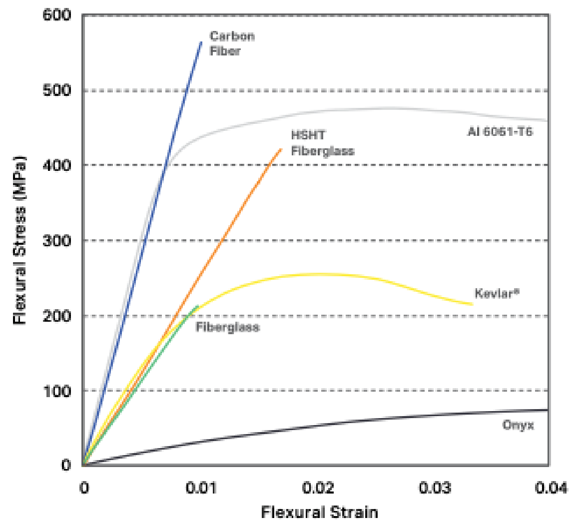

Figure 15.2. Kevlar ductility shown graphically.

3.8 Impact strength

Impact strength – also called impact toughness – is the amount of energy that a material can withstand when the said load is suddenly applied to it. It may also be defined as the threshold of force per unit area before the material undergoes fracture [38].

In contrast to some parameters already mentioned as tensile strength and yield strength, impact strength involves the application of force in mere milliseconds or less. The near-instantaneous implementation of load causes the material to absorb the energy. When the amount of energy exceeds that which it can accommodate, the material will experience fracture, tear, or damage. In this case, it can be said that the impact strength of the material has been surpassed [38].

Kevlar is 8x more impact resistant than ABS while remaining 15-20% lighter than our other reinforcement fibers.

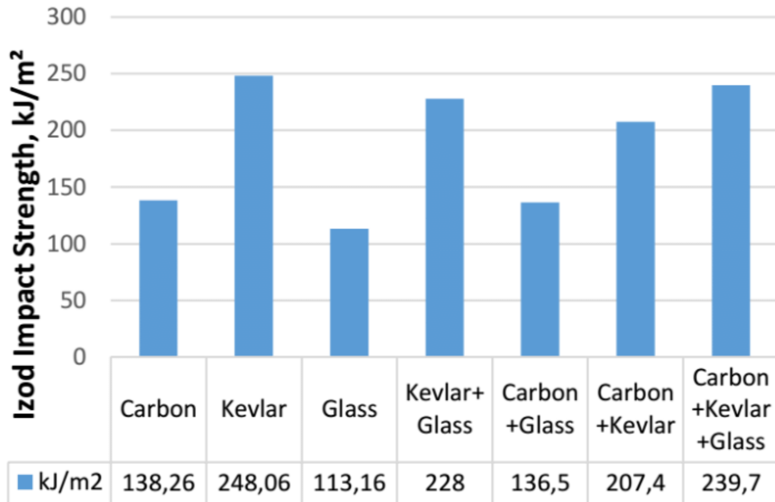

Table 6. Impact strength of composite specimens.

3.9 Fatigue resistance

Fatigue strength is the highest stress that a material can withstand for a given number of cycles without breaking. Fatigue strength is affected by environmental factors, such as corrosion. The maximum stress that can be applied for a certain number of cycles without fracture is the fatigue strength [40].

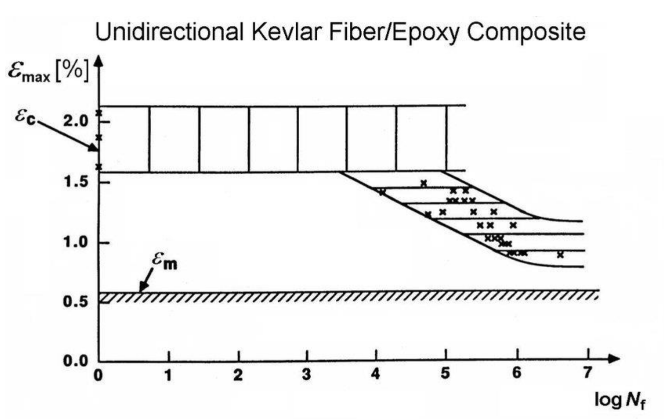

Figure 16. Fatigue life diagram of unidirectional Kevlar-epoxy composite

The tensile, creep and tension-tension fatigue properties of Kevlar-49 fibre (formerly known as PRD-49) have been determined. The fracture morphology of the fibre has been examined and is shown to be complex due to considerable splitting. The fibre quickly stabilizes under a steady load but failure due to creep can occur when it is loaded very near to its simple tensile breaking load. Kevlar-49 has been found to fail by fatigue, and its fatigue lifetime is dependent on the amplitude of the applied oscillatory load as well as the maximum load to which the fibre is cycled [39].

3.10 Hardness

Hardness is the ability of a material to resist deformation, which is determined by a standard test where the surface resistance to indentation is measured. The most commonly used hardness tests are defined by the shape or type of indent, the size, and the amount of load applied. The hardness numbers referenced constitute a non-dimensioned, arbitrary scale, with increasing numbers representing harder surfaces [40].
The two most referenced hardness test methods are Brinell hardness and Rockwell hardness, each one having a dedicated test machine with its own unique hardness scales [40].

Hardness correlates approximately with ultimate tensile strength [40].

Kevlar has high strength to weight ratio and ability to resist high impact they can be used as an alternative for metals. It is also said that sprinkling of Kevlar fibers on carbon composite reduces weight and boost its strength [41].

Sample No	Material	Hardness
1	Phenolic resin HR-6152	76
2	Glass fibre	39
3	Kevlar pulp	56
4	Carbon fibre	57
5	Friction modifier	55
6	Barium sulphate	42
7	Wollastonite	42
8	Talc	23
9	Graphite	22

Table 7. Scleroscopic hardness of individual component.

Studies have been developed to know more precisely the degree of hardness of Kevlar, and to investigate a little more about the mechanical properties of a Kevlar composite. In one of these investigations, four layers of Kevlar composite to be subjected to the Rockwell Test hardness.

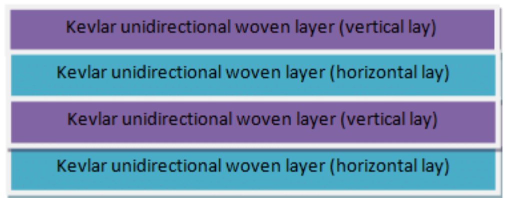

Figure 17. Fibre orientation of Kevlar composite

The results were positive. They concluded with very conclusive evaluations of Kevlar. They led to determine the good strength and hardness of the fibers of this polymer, hence it can be a good alternative material for automobile and other applications [41].

Sample	Energy absorbed(Joules)
Sample 1	32
Sample 2	33.4
Sample 3	32.8

Table 8. Result of impact test.

3.11 Failure Analysis and Prevention

Failure analysis is the science and technique of understanding how materials and products fail. Whenever a component no longer performs its intended function, it is valuable to understand how and why it has failed. Failure analysis is a critical part of understanding what went wrong, what could have been done to prevent the failure, and how one might prevent similar failures [42].

Any type of failure is, in nature, undesirable, but in some applications the consequences may go beyond inconvenience or cost, and may become critical or life threatening to the extents that even one failure, no matter how rare, would be considered unacceptable [42].

In the next study to be discussed, every composite joint was loaded until tear occurred. The general behaviour of the composite was obtained from the load/displacement curves [43].

Three types of load versus displacement curves were observed. These curves are almost linear until a sudden loss of load. Generally, the load reaches this value between 1.0 mm and 1.5 mm displacement. Some specimens tear immediately in this point. This failure mode is called as net tension, Figure 25 (a). For some specimens, the load decrease with increasing pin displacement and specimen tear. This failure mode is known as shear out, Figure 25 (b). For other specimens, the load then increases with increasing deformation and reaches the ultimate level. Following this, the load decreases with increasing deformation. But the specimen continues to carry loading. While failure area reaches 2–3 mm from the free edge of the plate in the direction of loading, then the plate tears immediately. This failure mode is named as bearing and shown in, Figure 25 (c). Although the joints carry on bearing load after the first peak the designer must ensure that the joint never reach the first peak load. Because the joints cannot recover its properties after this point [43].

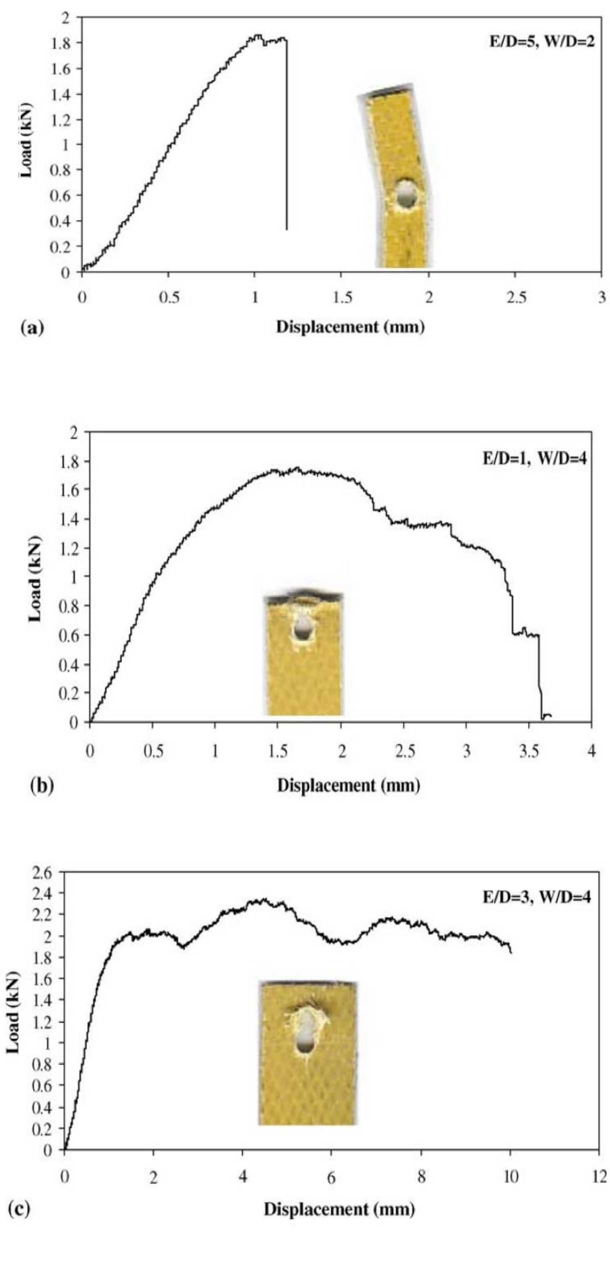

Figure 18. (a) Net tension, (b) shear-out and (c) bearing mode.

4. Manufacturing Process

The manufacturing process are the steps through which raw materials are transformed into a final product. The manufacturing process begins with the product design, and materials specification from which the product is made. These materials are then modified through manufacturing processes to become the required part [44].

The production of Kevlar fibers is similar to the production of nylon. The first step in the production process is to produce the basic chemical (poly-para-phenylene terephthalamide) which Kevlar is made of. The second step is the process of turning the chemical into strong fibres [45].

By the process of repeating amides over and over again, polyamides like Kevlar are made. Amides are chemical compounds in which a carbon-based acid replaces one of the hydrogen atoms in NH3. Polyamide is made by reacting an ammonia-like chemical with an organic acid. Thus, two substances are fused together into one by a process called condensation reaction [45].

The Kevlar artificial fibers should be spun just like natural materials, such as wool and cotton, in order to form a useful textile product. The process of wet spinning is used to turn the basic aramid into long, thin, and stiff fibers. This process forces the concentrated, hot, and very viscous solution of poly-para-phenylene terephthalamide through an orifice which in principles are similar to a bathroom shower head having several hundred holes. After the fibers cured, it is cut to length and woven into the desired application form (eg. ropes or bullet proof vests) which is a super-strong and super-stiff finished material [45].

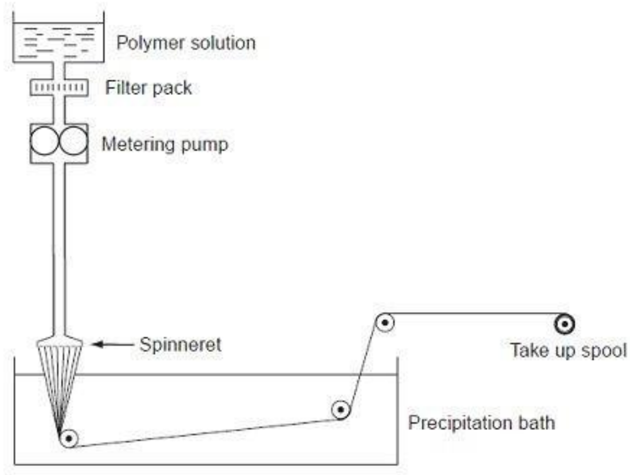

Figure 19. Diagram of Wet Spinning.

Kevlar is made from a condensation reaction of 1,4- para-phenylenediamine and terephthalic acid. The presence of amine groups on aromatic ring results in a rod-like structure which has high glass transition temperature and low solubility.
The chains of polymer are connected to each other via hydrogen bonding between adjacent polar amide groups explaining what Kevlar is. The fiber structure is consisting of orderly oriented molecules parallel to one another forming crystalline structure

Due to high glass transition temperature and poor solubility, these fibers are difficult to process via conventional drawing techniques hence melt spinning is used for their fabrication. During melt spinning, the PPD-T solution is extruded in a spinneret and drawn through an air gap resulting in the orientation of the liquid crystalline domains in the flow direction.
The polymer chains also align in a fiber axis resulting in a high degree of anisotropy in this direction.

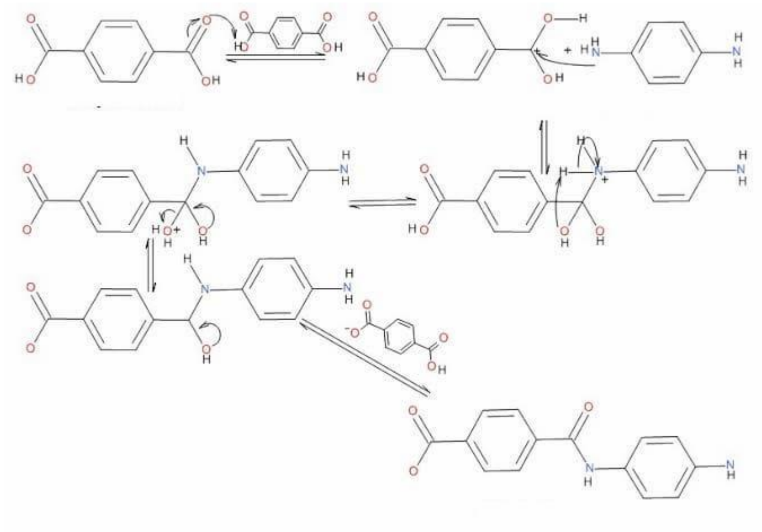

Figure 19.2. Condensation reaction for formation of Kevlar monomer.

In order to manufacture Kevlar with specified properties, dry jet wet spinning method is used by forcing a viscous fluid or solution of the polymer through the small orifices of spinnerets and immediately solidifying or precipitating the resulting filaments.

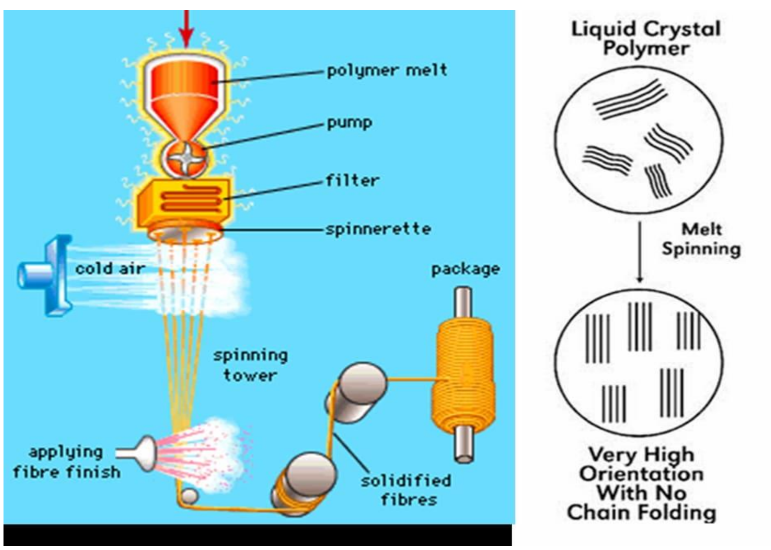

Figure 20. Condensation reaction of Kevlar.

5. Materials and Environment

Kevlar is very hard to destroy and if it is left to decompose in in a landfill it will not decompose for a very long time, if ever. Luckily, Kevlar is 100% recyclable and there are various companies, for example Ballistic Recycling, that specialize in the recycling of Kevlar. The picture below shows what Kevlar scraps look like in some of its various forms [47].

Figure 21. Kevlar chopped and ready to be recycled.

Kevlar production, on the other hand, has an environmental impact and is less sustainable. Sulphuric acid is one of the key ingredients in Kevlar processing. During the spinning phase, sulphuric acid is used to hold the Kevlar in solution. Sulphuric acid is extremely harmful to animals and plants, and if improperly disposed of or used, it may cause significant damage [46].

The use of concentrated sulphuric acid is also very hard and can thus also affect the sustainability of its use [46]. When Kevlar is recycled, it is chopped into 3-6 mm fibers and from there it can be respun, pulped etc. and formed into a new product. (Environmental Impact and Sustainability, 2016). Thus, once the Kevlar has been manufactured there is very little environmental impact, as long as it is disposed of correctly. That is to say that it is taken to a company that recycles Kevlar. Kevlar is very hard to destroy and if it is left to decompose in in a landfill it will not decompose for a very long time [46].

To summarize, Kevlar manufacturing can be hazardous to the environment and unsustainable, but it is safe if the proper protocols are followed. Kevlar is 100 percent recyclable after it has been manufactured and can be reused several times.

6. Cost Analysis

The high production cost of Kevlar was one factor that stymied its growth. Initially, DuPont was concerned that Kevlar would be more expensive than they could sell it for. To begin with, not just anyone can manufacture Kevlar. It requires the proper equipment to carry out the exact reaction needed to produce it. DuPont was able to produce Kevlar because it was an already established chemical company with both research and production facilities. Not many other companies, at the time, had the same resources that DuPont had [48].

Secondly, the reaction process calls for concentrated sulfuric acid to keep the polymers dissolved in the solution. Sulfuric acid is not only dangerous, but very expensive. Due to it being dangerous, it is expensive to handle and contain. Along with this, it is a painstaking process to get the sulfuric acid so concentrated, so there is another contributing factor to its high cost [48].

In addition to all these prior costs, there is also the cost of labor. Workers at DuPont were certainly not underpaid, which means that a lot of their profit goes to the hard-working employees. While it may seem unlikely for Kevlar to be profitable, the applications for it are so incredible that consumers were willing to pay the high prices [48].

Summary

Kevlar is a very promising up and coming advanced material. Kevlar is a heat-resistant para-aramid synthetic fiber with a molecular structure of many inter-chain bonds that make this polymer incredibly strong. Best known for its use in ballistic body armor, Kevlar also has many other applications because of its high tensile strength-to-weight ratio. Apart of an impressive level of strength which, in fact, this value is over ten times stronger than the steel's, pound for pound, its fibers also have excellent heat resistance, flexibility, ballistic resistance, cut/puncture resistance and really high durability, among other properties.

The chemical structure of Kevlar is comprised of several repeating inter-chain bonds. These chains are cross-linked with hydrogen bonds, providing a tensile strength 10X greater than steel on an equal weight basis.

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