Journal of Manufacturing Engineering, September 2015, Vol. 10, Issue. 4, pp 200-206

AN REVIEW ON ARAMID FIBER REINFORCED COMPOSITES

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ABSTRACT

Fiber reinforced polymer composite materials are becoming very popular and replacing conventional materials nowadays because of their excellent properties suitable for various applications a high degree of toughness and damage tolerance which leads to impact/ballistic performance. The properties of fiber reinforced polymers are comparable to most metallic materials like conventional materials. This is due to their lower density compared to the higher density in metals which leads to higher strength to weight ratio for the composites compared to that of the metallic materials. These composites are also easier to obtain desirable shape and require much less energy in making the required product. They consist of more than two constituent materials, the fiber material and the matrix material. There are number of fibers available for making composite material including synthetic as well as natural fibers. Synthetic fibers have been taken for lot of experiments whereas natural fiber is found to be less expensive and available plenty. Aramid fibers reinforced composites are used in many marine and aerospace applications where lightweight, high tensile strength, and resistance to impact damage are important. The fiber material is embedded in the matrix. In this review paper we look into the papers published taking various experiments and tests carried using mostly aramid fiber by different authors and discuss about the outlook of the various results.

Keywords: *Fiber reinforced polymer composite, Aramid fiber, Aerospace applications.*

1. Introduction

Aramid fibers are highly crystalline aromatic polyamide fibers. These are synthetic fibers that are man-made. They have one of the lowest density and the highest strength to weight ratio among the reinforcing fibers [1]. The most famous trade name for aramid fiber is Kevlar. They have a high degree of toughness and damage tolerance which leads to impact/ballistic performance. Aramid fibers do not fail by brittle cracking like glass or carbon fibres, they fail by a series of small fiber failures. These many small failures absorb much energy and, therefore, result in very high toughness [2]. They also have a negative coefficient of thermal expansion in the longitudinal direction. The main disadvantages of reinforced composites with aramid are their low compressive strengths and difficulty in cutting or machining. Aramid fibers reinforced composites are used in many marine and aerospace applications where lightweight, high tensile strength, and resistance to impact damage are important. Aramid fiber in the form of cloth is used in making bullet proof gear and other army equipment. Aramid fibers provide superior wear and lower friction coefficients.

Aramid fiber have a great load carrying capacity. Delamination is aramid fiber is not very obvious i.e visible [3].

Aramid fiber has the tendency to absorb water which leads to the decrease in it compressive strength [4]. Drying of fibre leads to its elongation and to some increase in the Young's modulus. The same is true for the effect of fibre irreversible strain Creep leads to an increase of Young's modulus of aramid fiber [5].

Fiber-reinforced polymer have self-lubrication properties. The abrasive wear resistance of fiber-reinforced materials has been found to be significantly lower than that of metals [6]. Fibre-reinforced thermoplastics (FRTPs), form an excellent class of tribo-materials because of their high specific strength and stiffness, properties available through controlled combination of fibre and matrix, combined with their excellent adhesive wear performance [7]. Aramid fibres have a low friction coefficient and high wear strength, and epoxy-based composite exhibit lower wear loss than polyester-based composite. The friction and wear of polymers can be attributed to two main mechanisms, deformation and adhesion. The deformation mechanism involves complete dissipation of energy in the contact area. The adhesion component is responsible for most of the friction of polymer and is a result of breaking of weak bonding forces between polymer chains in the bulk of the material and counterface or the transfer film [8]. The wear resistance of the material is determined using experiments in the laboratory.

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Machining of these materials is difficult. This is due to the reinforcement of fiber in the polymer matrix [9].

2. Methodology

Various different experiments and methods were conducted by the many authors reviewed in this paper. The main material used is the aramid fiber or Kevlar fiber that is made by DuPont. An image of the fiber is shown in Figure 1. The resins mostly used are epoxy, polyester, etc.

Fig.1 Aramid Fiber

Various different testing devices were used. For tribological purposes pin on disc setup , shaft on disc setup, block on ring setup, etc were used. For testing mechanical properties the most common equipment used is the Instron Universal tester. Other equipment were also used to test the various mechanical properties. Raman spectroscopy setup was used in certain papers. Scanning electron microscope was used to scan the various samples in order to identify inner defects, etc.

3. Literature Review

Anne Bolvari et al. [10] performed an experiment to determine the wear and friction of aramid fiber composite and aramid fiber composite with Polytetrafluoroethylene. They experimentally determined both mechanical and tribological properties of various combinations of fiber, matrix and PTFE. For optimum wear performance the weight of aramid fiber in the matrix is 5-15% wt. With the addition of PTFE the amount of aramid fiber for optimum wear performance increases to 20-25%. The increase in the content of aramid fiber also increases its mechanically properties.

Wu et al. [11] conducted an experiment to determine the tribological properties of Kevlar pulp in dry sliding and water lubricated conditions. Block on ring was used in the experiment. The material used was Kevlar pulp with epoxy resin. They concluded that the Kevlar pulp reduces the friction coefficient and specific wear rate in both conditions. Optimum quantity of the fiber was 40% of weight. Better friction reduction and antiwear behaviour was *observed* in the lubricated condition. Kukureka et al. [12] conducted experiments to identify the effect of friction and wear of of polyamide 66 with fibers under dry rolling sliding contact. They used three types of fibers – Glass, carbon and aramid fiber. The composites were tested using a twin disc machine. They identified that aramid fiber did not significantly alter the friction but both carbon and glass fiber reduced the coefficient of friction significantly.

Hasim et al. [13] studied the effect of load and speed on the wear behaviour of woven glass fabrics and aramid fiber reinforced composites. The experiment was conducted at two speeds - 500 and 710 rpm and at two loads – 500g and 1000g. The wear in the experiment was determined by the weight loss. The weight losses were measured after the different conditions. They came to the conclusion that applied load on the specimens has more effect on the wear than the sliding speed. Aramid fibres have a low friction coefficient and high wear strength, and epoxy-based composite exhibit lower wear loss than polyester-based composite, the wear of the aramid fibre-reinforced composite is lower than the woven glass fabric-reinforced composites. Davies et al. [14] studied the mechanical behaviour of high modulus polyethylene (HMPE) and aramid fiber ropes used for deep sea operations. The figure 2 shows us the image of the ropes used for testing.

A small number of single fibre tests were performed in a Dynamic Mechanical Analyser. Then tensile tests were performed on full size rope samples. Both ropes have advantages and disadvantages and both are currently in use on oceanographic vessels. The aramid rope stiffness is less sensitive to bedding-in and shows lower permanent residual strains. It also creeps less. The HMPE rope is lighter and stiffer after bedding-in with higher damping. Resistance to cyclic loading on sheaves is superior for dry aramid but experience from tests on soaked aramid and aramid is not as good as that of wet HMPE.

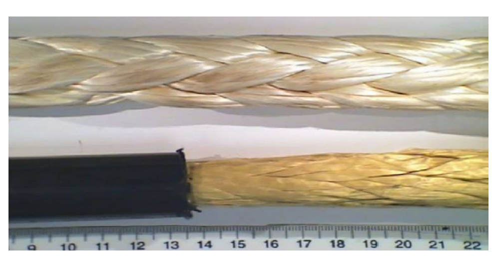

Fig. 2 Handling rope - HMPE (upper), Coated aramid fiber (lower)

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Measurements of apparent stiffness at sea appeared consistent with laboratory values. Resistance to cyclic loading on sheaves is superior for dry aramid but experience from tests on soaked aramid and in-service experience suggests that wet fatigue behaviour of aramid is not as good as that of wet HMPE. Measurements of apparent stiffness at sea appear consistent with laboratory values, but loading history and in particular the maximum load seen previously by the rope determines the apparent stiffness.

Jang et al. [15] discussed about the effect of impact behaviour on polymer composites including aramid fiber polymer composite. One of the samples used was a combination of aramid fiber and epoxy resin. They subjected the material to repeated low velocity impacts. Their failure mode versus loading history relationship was examined. They came to the conclusion that impact test can be used to identify the damage tolerance of the composite. There exists a critical incident energy, above which significant damage in the form of a delamination crack will occur to the composite in response to a single impact. Impacts below the critical energy will not cause delamination. But when repeated impacts continue after delamination initiation, the delamination cracks grow in size and number, leading to a continuing loss in the strength and stiffness of the composites.

Hao Cen et al. [16] found the effect of geometry on interfacial micromechanical behaviour of fiber/matrix micro droplets is investigated by means of the combination of microbond test and Micro-Raman spectroscopy in this paper. Microbond test is usually employed to measure the interfacial properties of fiber/matrix composites. Micro-Raman spectroscopy is introduced into the microbond test to detect the distributions of micromechanical properties including fiber axial stress, residual stress, interfacial shear stress and stress transfer length along the interfaces between Kevlar-29 aramid fiber and epoxy resin matrix microdroplets.

The mechanical properties of fiber/matrix interface are affected by the geometrical characteristics of the microdroplets. A larger interfacial edge angle of the microdroplet always corresponds to a shorter stress transfer length and sharper decreases in both fiber axial stress and interfacial shear stress along the fiber, as well as a greater shear stress concentration at the interfacial end point, which implies a greater risk of interfacial failure and breakage. The residual stress should not be neglected in the microbond test and succeeding analysis. Furthermore, both the distribution and magnitude of the residual stress are also affected by the geometrical characteristics of the microdroplet.

Marom et al. [17] investigated the fatigue behaviour on hybrid composite materials. The materials used were the parent aramid fibre and carbon fibre reinforced composites and sandwich hybrids of aramid/carbon/aramid and carbon/aramid/carbon with different ratios between skin and core thicknesses. Epoxy resin was used. The specimens were loaded for fatigue testing in an Instron Universal Tester. Fatigue behaviour was studied by them by cyclic loading at relatively high stress amplitudes, with Stress varying from a minimum of 7-10% to a maximum of 70-100% of the static strength. Incremental loading tests were conducted under strain control conditions. They concluded that Aramid fibre/carbon fibre hybrids of the ACA type, namely sandwich hybrids with aramid fibre-reinforced skin and carbon fibre-reinforced core, exhibit a positive hybrid effect in their flexural strength. An explanation for the positive hybrid effect in the flexural fatigue of ACA hybrids may lay with the strain rate dependence of failure in these materials. With compressive failure being the active mode of failure in these materials under both static and fatigue conditions, the respective properties are expected to be a direct function of the compressive strength. The latter is extremely strain rate dependent, as shown by compression data derived from the flexural results and hence, the rate sensitivity of the ACA hybrids.

Briscoe et al. [18] studied the effects of fabric weave and surface texture on the interlaminar fracture toughness of aramid fiber/epoxy laminates. Two types of fabric weaves were chosen – plain weave and satin weave. The fracture toughness was evaluated by using a double cantilever beam specimen configuration. They concluded that the range of fabric properties affected the toughness of the composite. The type of fabric weave has a small effect on fracture performance, with plain-weave fabrics showing slightly improved performance relative to satin weaves.

Kazuto Tanaka et al [19] performed single fiber pull out tests to investigate the influence of water absorption on interfacial properties on the interfacial properties of aramid/epoxy composites. They performed Pull-out tests using an electrohydraulic servo controlled fatigue testing machine. Single fiber pull-out tests were successfully applied to quantitatively analyze the influence of water absorption on the fiber/matrix interfacial properties. The interfacial strength of aramid/epoxy composite was decreased by 26% after 7 week immersion time. The interfacial strength was drastically changed between 4 and 7 week immersion time and showed the plateau thereafter. The change of the interfacial strength with immersion time did not correspond with that of the water gain in pullout specimens, because the water gain did not reflect the one in the fiber/matrix interface. As a result of degradation of the fiber/matrix interfacial strength by water absorption, 7, 10 and 13 week wet specimens were fractured by adhesive failure with interfacial crack and the fiber surface looked smooth.

Krystyna Imielinska et al. [20] subjected glass–aramid-fibre/epoxy laminates to water immersion and followed it by low velocity immersion test. Internal damage was highlighted by backlighting the impact site and its size measured using an image analyser. Compression-after-impact (CAI) tests evaluated the damage tolerance of the composite, which refers to the ability to tolerate a specified amount of damage. The laminates were subjected to water immersion ageing followed by low velocity impact. Water immersion ageing affected microstructural integrity of the two composites causing numerous internal defects. No important effect has been found of aramid–glass fibre configuration on moisture absorption and impact tests characteristics. Threshold damage (fibre/matrix debonding) load was very low and independent of laminate lay-up or conditioning. Due to low fibre–matrix adhesion, the prevailing impact failure modes were fibre/matrix debonding and interfacial cracks. Impact damage area was slightly less extensive in wet samples, which is suggested to be the result of the propagation of interfacial damage present in wet samples prior to impact, which absorbed impact energy and inhibited the delamination formation.

Reis et al. [21] investigated the impact behaviour as well as damage tolerance of Kevlar with epoxy matrix. Two different fillers, cork powder and nanoclays Cloisite 30B, were used by them in order to improve the impact response of these laminates. Low-velocity impact tests were performed. Cork powder and nanoclays Cloisite, were used in order to improve the impact resistance of these laminates. The fillers adding increases the maximum impact load, which is very dependent of the filler type for high impact energy. For 21 J the maximum load increase about 4.5% for laminates filled by cork, 10.4% for laminates filled by cork/clays and 16.1% for laminates filled by clays. The opposite tendency was observed for the displacement, where the nanoclays are the fillers that promote lower values. The best performance in terms of elastic recuperation was obtained for laminates manufactured with epoxy resin filled by nanoclays.

Bennett et al. [22] used raman spectroscopy to study the effect of matrix cracking on the deformation micromechanics of untreated and adhesion-activated aramid fibres embedded in an epoxy matrix. Two varieties of twaron fibers were used by them- high-modulus, completely untreated (HMU), i.e. without size or finish; and high-modulus with a commercial surface activation (HMA), i.e. treated with an adhesion-active finish formulation. They have shown that dynamic crack propagation perpendicular to an array of aramid fibres in an epoxy resin matrix leads to debonding for both untreated and adhesion-activated fibres. The fibres are found to bridge the crack with no fibre fracture. The micromechanics of fibre deformation during subsequent reloading depend upon the level of adhesion at the fibre/matrix interface. Debonding was propagated further during reloading for the system containing untreated (HMU) fibres, whereas in the system containing adhesion-activated (HMA) fibres, further debonding did not occur. In addition, it was sometimes found that the debonding was asymmetric about the crack plane for the adhesion-activated fibres. It has also been shown that that debonding may occur for fibres ahead of or at the crack tip for the HMU fibres. In contrast, the HMA fibres exhibit no such debonding and the interface appears to remain fully intact.

Othman et al. [23] investigated the effect of different designs of aramid fabric on the ballistic performances. Kevlar Argus and Gold Flex (GF 4) fabrics are used. Each sample of Kevlar Argus and GF 4 were prepared in five sets of panels, consisting of 1, 5, 10, 15 and 20 layers accordingly. For the energy dissipation study, the optimum design of textiles was observed due to the higher energy absorbed by the fabrics. At 5 and 10 layers of fabric, it was found that the cross-ply construction absorbed 17% and 90% respectively. Material strength was observed to increase proportionally with the increasing number of layers. From the analysis, the ideal number of layers can be determined for total (i.e. 100%) energy dissipation based on the optimized equations. The cross-ply aramid laminates only required approximately 16 layers for 100% energy dissipation and 18 layers for those of their woven counterpart. In addition, the post-impact projectile deformation has further proven that the cross-ply configuration was able to arrest the projectile at an earlier number of ply layers.

Wong et al. [24] introduced an innovative method to increase ballistic performance of the material. Ballistic test samples of aramid fibre (Kevlar 29) and ultrahigh molecular weight polyethylene (UHMWPE) were sandwiched by two sets of opposing magnets. This study demonstrates that the ballistic performance with the effect of a magnetic field has a strong energy of repulsion force. No perforation or fracture of aramid fibre was observed when magnetic field was generated at the target. The aramid fibre incurred minimal damage which can be further reduced if higher strength magnets were used. The UHMWPE ballistic tested showed the repulsion force was not as strong as is in the aramid

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fibre owing to the large standoff distance between the two opposing magnets.

Ying wang et al. [25] presented a detailed finite element analysis to investigate numerically the ballistic impact resistance of multi-fabric panels. The FE model was created using ABAQUS to simulate the transverse impact of a projectile onto various woven fabric panels. Influencing factors were taken into consideration. The numerical predictions show that the orientation of plies significantly affects the energy-absorbing capacity of the multi-ply fabric panels. The angled panels always increase the energy-absorbing capacity, compared with the aligned panel, by as much as 20%, depending on the number of plies in the panel. In addition, the stacking sequence of oriented plies also plays an important role in absorbing the energy. For the multi-ply fabric panel with large numbers of plies, there is an optimised sequence of plies which can maximise the energy-absorbing capacity of the panel. An important aspect of the work is validation of the numerical technique. It is shown that the FE predictions are highly consistent with the experimental study.

Khalili et al. [26] investigated the effect of reinforcing the adhesive on the creep behaviour of single lap joints. Three types of fibres - aramid, carbon and glass were used. The test was performed at a temperature above the glass transition temperature of the adhesive. Creep behaviour of reinforced adhesive joints was studied in this paper. According to the specimen fracture surfaces, it can be seen that in the fibre reinforced adhesively bonded joints, in addition to the adhesive failure, fibre fracture failure was also occurred, which means that fibres were stressed to their ultimate tensile strength. The initial strain in all specimens was considerably decreased for all reinforced adhesives, independently of the fibre type and orientation. Fibre's orientation had no significant effect on the initial strain. The failure time was largest for carbon reinforced joints. Aramid fibre showed better results in terms of failure time and strain rate. Due to adhesives weakness in tolerating high temperatures, it is recommended to add fibres in the bondline which considerably enhances some of the mechanical properties of the joints, specially the creep behaviour.

Fischer et al. [27] studied the flexural behaviour of aramid fiber composite. They used hybrid composites of aramid, carbon and glass. For the case of aramid fibres in the skin the analysis predicts the type of fracture, namely, a tensile fibre fracture in the skin or compressive core fracture at the core-skin interface. For both glass and carbon fibre cores, reducing the skin thickness reduces the shift of the neutral axis at fracture, and increases the bending stress for fracture.

Andrews et al. [28] performed tests to report the application of raman spectroscopy to determine the distribution of fiber strain in fragmentation, pull-out and microbond test pieces. They performed tests on both Kevlar 49 and Kevlar 149 with epoxy. Raman spectra was obtained during deformation of the composite. In this paper they have demonstrated that Raman spectroscopy is a powerful method of analysing the micromechanics of fiber deformation in composite test pieces as those used for fragmentation, pull out and microbond test. It provides and unique information concerning the point to point distribution of fiber strain in the specimens and it has been shown that the behaviour is very dependent upon the specimen geometry.

Masaru Mori et al. [29] modified the the surface properties of aramid fiber by graft polymerization of acrylamide and glycidl methacrylate on the surface of the Kevlar 49 surface. Kevlar 49 was employed as the aramid fibre for surface modification. The plasma treatment of the fibre was performed in a bell-jar-type reaction cell. After removal of homopolymers, the grafted fibre was subjected to surface analysis with attenuated total reflection Fourier-transform infra-red irradiation. The reaction of proplyamine with the grafted surface was accompanied with the appearance of new nitrogen peaks in the XPS spectrum suggesting the presence of epoxy groups on the surface of the PGMA - grafted fiber.

Wang et al. [30] studied the effect of low velocity impacts on 3d woven basalt/aramid hybrid composites. Samples were prepared with both interply and intraply. Their low velocity impact properties were tested. The interply hybrid composite had higher ductile indices, lower peak load, and higher specific energy absorption in both warp and weft directions than those of the intraply hybrid composite. The load time curves of the interply hybrid composite showed a step by step decrease of the load while those of the intraply hybrid composite showed a more sudden drop of the load. Postmortem photographic analysis indicated that interplay hybrid failed in a layer-by-layer mode, leading to much larger energy absorption, while intraply composite showed a brittle mode, resulting in significantly lower energy absorption.

Huang Gu [31] investigated the tensile behaviour of various fibers after treatment with NaCl. The materials used were quartz, aramid and glass. The tensile test was checked before treatment and after treatment. It was concluded that NaCl is powerful enough to break down the molecular chain in the fibers and reduce tensile strength. Aramid fiber had a drastic reduction in tensile test after it was treated for 3 weeks.

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Zhi Sun et al. [32] investigated the effect of adding aramid fiber to brittle epoxy joints between carbon fiber and aluminium substrate. The fibers were chopped into small pieces. The interfacial fracture toughness and toughening mechanisms of carbon-fibre and aluminium-substrate laminar composites with and without short aramid-fibre toughening have been measured it can be concluded that the interfacial toughening from the short aramid fibres is effective. The in-situ formed "composite adhesive joints" due to the presence of short aramid fibres can enhance the interfacial toughness through crack-bridging and deflection within the adhesive joint,and protruding fibre ends onto the carbon-fibre face-sheet surface.

4. Conclusion

A clear review on aramid fiber reinforced composites is given. The various properties of aramid fibers have been discussed. From the survey made it is clear that aramid fiber have superior strength to weight ratio and toughness when compared to other common synthetic fibers. They have low coefficient of friction and high wear strength. Thus aramid fibers have properties which are best suitable for gear meant for protection from wear, impact and temperature.

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