Cairo University

APPLICATION OF SHORT FIBERS REINFORCED COMPOSITES IN POWER TRANSMISSION COUPLING

By

Kareem Saeed Abdel-Wahab Ahmed Hamza

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Design and Production Engineering

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Title of Thesis:

Application of Short Fibers Reinforced Composites in Power Transmission Coupling

Key Words:

Short Fibers; Coupling ; Simulation ; Design of Experiments ; Finite Element Analysis

Summary:

In this study the use of short glass, carbon and hybrid glass-carbon fibers reinforced polymeric composites in 3D bulky loaded composite materials is investigated. An application of a rigid coupling is used to predict the limiting torque values based on the fibers properties , distribution, percentages, and orientation. The effects of the constituents weight percentages, and average fibers length on the composite tensile strength and modulus are studied using the Taguchi design of experiments method. A new approach of finite element analysis "FEA" is introduced to model the effect of the hybrid fibers random distribution and average fibers length along the volume of the matrix. The FEA model is applied on the tensile specimen and then on the power transmission coupling simulation. The Modeling technique is validated with the design of experiments. Different failure criteria are studied on the tensile specimen model and on a 3D loaded representative volume element with controlled fiber orientation and loading direction. Finally, the coupling suggested FEA modeling results are compared with the conventional isotropic simulation.

Chapter 1 : Introduction

Power transmission coupling and other mechanical transmission elements are usually manufactured from steel that results in relatively heavy products. In automotive, airplanes, space and other automobile applications light power transmission elements are required to reduce the energy consumption. Steel alloys are perfect when high strength and rigidity are required, and the weight is not considered. On the other hand there are many applications where high strength and rigidity are required but also with light weight. The very common applications for such requirements can be found in automobile, automotive, aero-plane, aerospace, and sports industries. Plastics provides very light weight, but the strength and rigidity are not always satisfactory. Only Composites can provide a tailored materials with a satisfactory combination between strength, rigidity, and light weight.

Short fibers reinforced thermoplastic or thermoset composites are widely used in 3D loaded bulky materials to provide higher strength and rigidity to weight ratios. The majority of the available micromechanical models are only valid for laminates and in-plane loaded structures. There is a need to have a model that describes the design limiting criteria for 3D loaded bulky composites. K. Zhu used the combined cell model to simulate the mechanical behavior of short fibers reinforced composites with a metal or plastic matrix with small strains. He also presented the statistical combined cell model to predict the failure properties of short fibers reinforced composites **[1]**. He also concluded that the combined cell model doesn’t provide the enough accuracy for the failure condition **[1]**. Shao-Yun Fu also studied the effect of the particle size and interface adhesion with the matrix on the mechanical properties of the particulate-polymer composites **[2]**. S. Kammoun analyzed the progressive failure of short glass fiber reinforced thermoplastics on different levels **[3]**. He started the study from a representative volume element, then a homogenization to the fibers properties and the grain modeling. Finally, the damage modeling and final homogenization is performed to represent a representative volume element with homogenous mechanical and failure properties.

M. Eftekhari presented a fatigue modeling technique of filled short glass fibre reinforced Polypropylene and polymaide-66 composites **[4]**. The study included the effect of the temperature an mean stress on the fatigue life time of the composite. The effect of the mean stress showed a significant effect on the fatigue life on the studied materials at various temperatures. Although a general fatigue life prediction was predicted by Eftekhari's model, an average homogenous material was estimated. In this research we are applying a micro- modeling on the composites where each fibre will be simulated independently. This enables us to better understand and use the model of fatigue life cycle and how to optimize and enhance our design. Janis Sliseris introduced a numerical modeling of a flax short fibre reinforced and flax fibre fabric reinforced polymer composites **[5]**. Janis could model the microstructure of short fibres and its length to diameter ratio using a predefined algorithm, then the fibres were simulated using a tetrahedron 4-node finite elements **[5]**. The simulation could capture the main damage mechanisms such as fibre breakage. The simulation depended on using the representative volume elements, without proceeding to 3D loaded bulky parts.

Marika Eik introduced an experimental approximation for the fibres orientation distribution function **[6]**. She also studied the effect of the approximation accuracy on the elastic properties of the composite. They concluded that the effect of the orientation distribution accuracy on the stiffness matrix should be taken into consideration in the finite element modeling of fibres reinforced composites. Thus, a detailed modeling of the fibres length and also distribution is needed for a reliable simulation results. M.Ncin proposed a model for the viscous behavior of short fibres reinforced composites **[7]**. The composite was modeled as an assembly of matrix medium with a set of linear elastic elements. The study of the macroscopic properties of the composite showed a significant effect for the different strain rates. M. Ncin's model was also validated results with experimental results on fibreglass reinforced polypropylene. Ncin's model haven't discussed also the 3D loading effect as well. Notta Cuvier investigated the impact of flax fibres properties variability on numerical tensile behavior of short fibre reinforced polypropylene composites **[8]**. The in-plane random and aligned distribution of the fibres showed a significant effect on the composite properties. Although short natural fibres are not a high performance composite, but modeling the distribution properly showed a dramatic change in the properties of the composite. The tensile strength changed from a lower bound to the upper bound to three times just by changing the fibres distribution. K. Senthilkumar discussed the inter-laminar fibre orientation effect on the tensile properties of composites **[9]**. Only aligned in-plane fibers were studied without proceeding to 3D loaded bulky materials. Different fibers orientations and compositions were fabricated using the compression molding technique, and their tensile testing was used in the validation of the modeling results.

Another application for short fibers modeling was investigated by A. Dean where a hybrid metal composite clinching joint were studied **[10]**. Aluminum alloys - short fiber reinforced polymers clinching joint was simulated to validate the use of finite strain constitutive formulations**[10]**. The modeling technique presented by A. Dean also investigated an in-plane distribution of the fibres within the matrix. The simulation presented by A. Dean need to be generalized to 3D loaded bulky shapes.

A. Ayadi reported a new approach for modeling the macrostructure properties of injected short glass fibres reinforced polypropylene using a 3D imaging technique **[11]**. The imaging technique was implemented based on the X- ray micro tomography. The modeling technique studied figured out the effect of injection flow directions and other factors on the final orthotropic properties of the composite. The reported properties was used in a second finite element computation to simulate the heterogeneous structure of the composite. This study showed a great approach for micro-modeling of 3D loaded shapes, but using an expensive X ray tomography. The validated technique by this study is a good caliper to proceed in the modeling of the design criteria of short 3D loaded bulky shapes. D. Notta presented and original model of fibre complex distributions of orientations without averaging or homogenization **[8]**. Notta modeled the matrix with an elastoplastic damage, and the fibers with a ductile damage scenario **[8]**. The model was also validated using short flax fibres reinforced polypropylene. The model presented by Notta haven't discussed the interfacial bonding properties between the fibres ad the matrix which can have a great effect on the composite limiting design stress or strain values **[8]**.

1.1. 3D Fibers Embedded Modeling Failure Criteria

The modeling technique can be used to predict the local stresses on the matrix elements, and the local stresses on each fibre, and the element average composite stresses. in addition to this the principles stresses on both the fibres and matrix can be reported. Different limiting stresses design criteria can be studied to predict the coupling failure based on one of the following stresses:

1. Local stresses on fibres
2. Interfacial stresses between the fibres and matrix
3. Average composite stresses
4. Hashin fibre damage
5. Hashin matrix damage

Each model can be used to predict the failure, for more conservative design we can conclude that the composite will fail if any of the studied criteria exceeded their maximum limits. Each failure criteria will be discussed here. The tensile specimen will be loaded gradually, and the three studied parameters will be measured.
Due to the difficulty of estimating the composite average strength and fibre local strength, the interfacial stresses failure criteria is the most common and reliable one. H Wang studied the interfacial stresses between a fibreglass embedded within an epoxy matrix **[12]**. Wang studied the elastic deformation of both the matrix and fibre by micro-indentation to the center of the fibre by gradual increased load till the micrograph analysis showed a failure displacement for the fibre within the matrix. M. Tarfaouli and K. Bsisu used the Hashin damage criteria embedded in Abaqus for modeling composites laminates damage **[13,14]**. In this study we will use the method of Hashin damage on 3D loaded fibers reinforced composites, which is not the conventional way of Hashin damage usage. This will be conducted by simulation the random discontinuous 3D fibers as a set of layers with all orientations and homogenous distribution.

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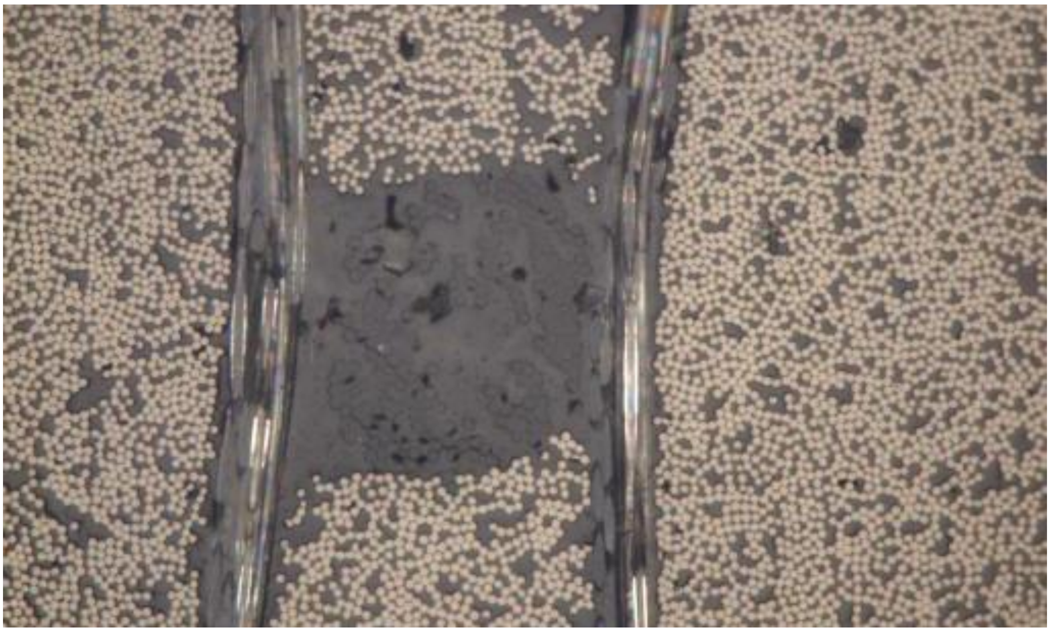

Figure 1.1. Optical micrograph for two fiberglass bundles within an epoxy matrix after failure due to center micro indentation [12]

1.2. 3D Loaded Fibers Reinforced Composites Design Stress Mathematical Modeling

In this section the mathematical models for describing the loading stress of a 3D loaded fibers reinforced composite will be described. A general fiber orientation is defined with respect to the forces loading directions. Figure **(1.2)** shows a representative volume element of fibers distributed with a matrix medium. The fibers have a certain length and orientation within the 3D space. Each fiber has angles α, β, γ with respect to the *x, y* and *z* axis. The loading is distributed in the 3D directions and also defined as follows:

$$\sigma_x = \sigma \quad , \sigma_y = k_1 \sigma \quad , \sigma_z = k_2 \sigma \tag{1.1}$$

The loads will result in local stresses on the fibers, the matrix, and on the interfacial shear stresses between both fibers and matrix, then these values of stress should be compared with their limiting strength or design values.

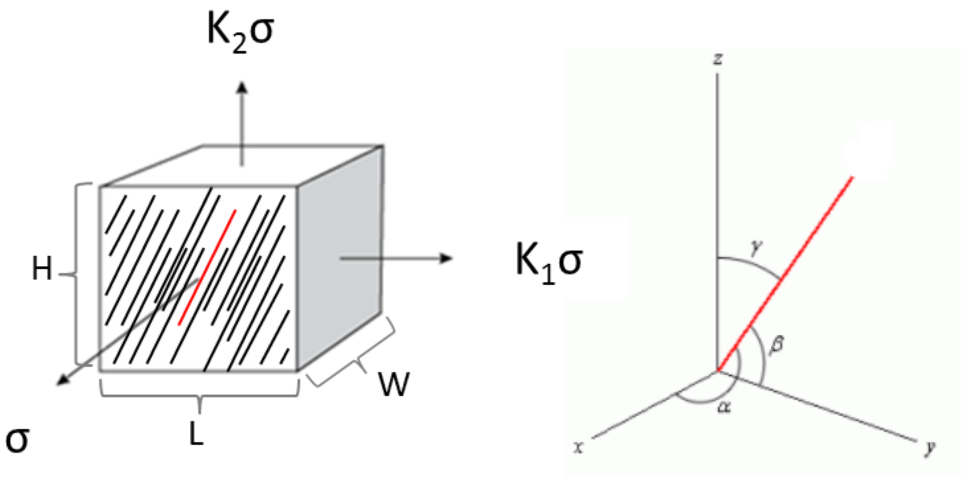

Figure 1.2. Fibers Orientation with 3D loading in a fibers reinforced composite RVE

Figure (1.3) shows a representative volume element where a fiber is loaded within ts surrounding matrix medium. The tensile strength should be studied as a function of S_{limit} = f ($(k_1, k_2, \theta_1, \theta_2, L_f)$ and from H. Wang the interfacial bonding strength equation [**12,15**]. Eq. (1.2) can be used to calculate the interfacial bonding strength.

$$\tau_c = \frac{n.P_C}{2.\pi.r^2}, n^2 = \frac{2G_m}{E_f \ln(R_e / r)} \qquad (1.2)$$

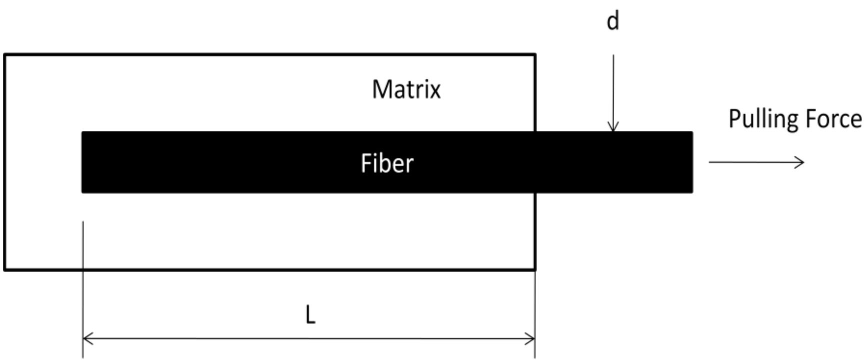

Figure 1.3. Pulling force of fibers within the matrix [15]

where T_c, P_c, r, R_e, G_m, and E_f are the bonding shear strength, critical pulling force, fibre radius, distance between two fibres, matrix modulus of rigidity, and fibre young's modulus. The distance between the fibres can be calculated as an average value using the following equation:

$$R_e = \frac{V_c - V_f}{H\,W\;L\,N} = \frac{L}{N} - \frac{\pi r^2 L_f}{H\,W} \qquad (1.3)$$

And according to Won-Chang Choi the critical force that causes deformation to a fibre embedded within a matrix can be calculated from the following formula as in Eq. (4.1) [**16**].

$$P = \sqrt{\pi \tau_o E_f r^3 (1+\eta) \delta_o + \pi G_d E_f r^3} \qquad (1.4)$$

where δ_o is the fibers critical deformation**.**

1.3. Short Fibers Reinforced Composites FEA Modeling

All the available finite element analysis model the short fibers reinforced composites in mechanical 3D loaded applications as an average isotropic materials, without defining the fibers distribution, length variations, orientation, and concentration distribution. V. Subrahmanyam presented a very recent simulation of a glass fibers reinforced epoxy composites to determine the elastic properties of the composites **[17]**. The simulation was conducted using a representative volume element having the necessary boundary conditions. Figure **(1.4)** shows the representative volume element got from a hexagonal array aligned fibers reinforced composites.

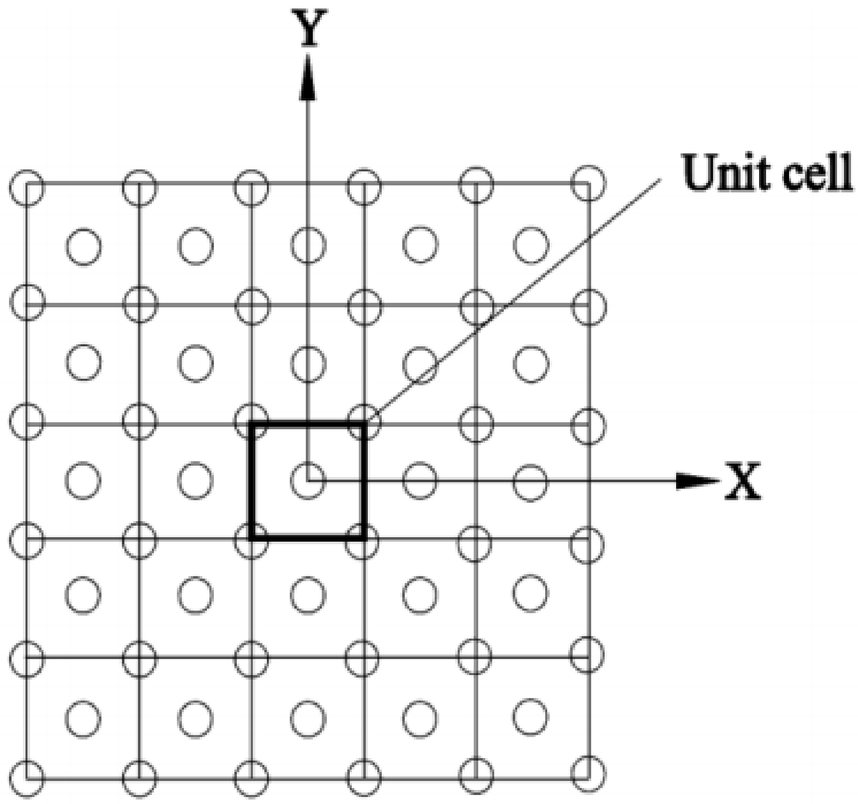

Figure 1.4. Representative volume element simulation of a hexagonal fibers array [17]

This kind of average properties simulation seems to be accepted since the majority of used short fibers reinforced composites have low strength and modulus. Some applications where high performance carbon fibers are embedded with high epoxy modulus with a high fibers volume ratio. The available micromechanical models also deal with the short fibers reinforced composite as a representative volume element when simulated. In this research a new approaches will be introduced to simulate the fibers orientation and length in the 3D space with the matrix filling the volume of the shape being simulated. Then a controlled algorithm will enable the designers to control the following parameters:

1. Fibers type, properties, and volume percentages
2. Fibers length variations
3. Fibers orientation
4. Fibers distribution and concentration
5. Interfacial relation between the fiber and matrix

This simulation technique will enable the designers to tailor the required composite according to the required mechanical properties. It will also equip them with a tool to simulate the composites with preferred directions and fibers concentrations. Some processing technique reduce the average fibers length in some areas in the produced part, and increase the concentration of the longer fibers in other areas. All this need a simulation based algorithm where each fiber will simulated independently.

Chapter 2 : Literature Review

2.1. Introduction

Composite couplings provide good features including corrosion resistance, high-misalignment capacity, excellent fatigue resistance, low weight, and ease of installation **[18]**. Fibers reinforced composites are good solutions where high properties are combined with light weight benefits. Short Fiber reinforced thermoplastics can be used in many applications with the same manufacturing techniques used with unfilled plastics. Fibers reinforced plastics are increasingly used in plastic injected products due to their high their enhanced specific stiffness, and strength **[19]**. The prediction of short natural fibers composites mechanical properties is very critical and should depend on experimental work. P.J. Herrera-Franco studied the interfacial properties between natural fibers and High density polyethylene **[15]**. The results showed great deviation and nonlinearity in the properties due to the many parameters affecting the interfacial bond strength. This complexity requires better simulation technique in order to reduce the required number of experiments needed to know the properties of the composite. Many researches are being conducted on studying the effect of fibers addition to polymers through pallets injection, powder injection, and compression molding. The influence of orientation of short carbon fibers in composites in powder injected composites on the shear properties is studied experimentally by Shirazi to enhance the composite properties by controlling the flow parameters in the powder injection technologies **[20]**. The properties of the short fibers composites are dramatically dependent on the orientation of the fiber to the direction of the measured properties. Seyyedvahid M., and Fatemi A. studied the anisotropy effect of the measured properties in the tensile test between the inflow direction of injection and perpendicular direction **[21]**. Their results showed a significant drop in the tensile strength and modulus of the perpendicular direction compared to the inflow direction. The Influence of reprocessing on fiber length distribution, tensile strength and impact strength of injection molded cellulose fiber-reinforced polylactide (PLA) composites was conducted by Graupner, N. et.al **[22]**. All the conducted researchers showed a dramatic effect for the fibers type, alignment, length, and processing parameters on the composite performance **[23]**. This research shows a new approach of modeling the short fibers reinforced composites, where each fiber is simulated independently; and the results can be visualized on the each type and segment of used fiber even with hybrid fibers composites. The problem of the available micromechanical models is the inability to accurately predict these composites' properties, performance, and durability **[24]**. Depending on these available models of random discontinuous fibers composites in determining the composite properties epically with 3D loaded shapes is not practical. The reason is that these models deal with the composite as a homogenous material with average properties **[23]**. The suggested simulation technique doesn't only provide better practical estimates of the composite performance, but also provides a powerful tool of optimization. The hybrid fibers percentages, inhomogeneous distribution and average length can be used as design optimization parameters. The objective of the optimizing process is to get closer to the required tensile and young's modulus values.

In this research paper, the experimental and modeling results are analyzed using the design of experiments Taguchi method. Three parameters effects are studied using 3 levels per each to present the nonlinearity and interaction effects of each parameter on the studied responses. A new Finite element model is presented to predict the composites behavior under the tensile test conditions according to the ASTM standard **[24]**. Bocheng presented a 3D simulation for a representative volume element of longitudinal and random fibers reinforced composites **[25]**. Kenik presented the theoretical background behind the structural FEA of fibers composite produced by the plastic injection method **[26]**. Robbins used the theory of Doug and the features of Autodesk to produce random fibers distributed in injected plastics products to model biaxial loaded problems **[27]**. In this research the presented finite element model is generalized to all fibers types, lengths. More researches were conducted to check the processing parameters and effect on the product average fibers length and orientation since this will dramatically affect the properties being simulated. Akira I. studied the effect of the screw design on the resulting average fibers length of the glass fibers injected polypropylene **[28]**. The study of the processing effects on the products can be a guidance to our simulation parameters for a more validated simulation compared to the properties of experimental samples with much longer fibers. Both thermoplastic and thermoset matrices are also applicable on the model. The interaction between the fibers and the matrix is also defined. The local stresses on the fibers are recorded and the average on the composite as well. Hybrid carbon-glass fibers reinforced epoxy with the design of experiments factorial design is experimentally performed on 9 runs with 3 replications each. The same runs are also performed using the FEA model. The results of both the experimental and model runs are compared to validate the FEA model. Using the design of experiments technique, an analytical mathematical model is presented to predict the composite tensile strength and modulus as a function of the studied three parameters nonlinearly.

The majority of the available micromechanical models are only valid for laminates and in-plane loaded structures. There is a need to have a model that describes the design limiting criteria for 3D loaded bulky composites. The FEA introduced here in this study shows the results on each fiber and on the interfacial bonding between the fibers and the matrix. The model was also experimentally validated and tuned for manufacturing and fibers defects values. This model will be used here to get the limiting design criteria for any 3D loaded representative volume element of the composite. (K. Zhu, 2003)used the combined cell model to simulate the mechanical behavior of short fibers reinforced composites with a metal or plastic matrix with small strains. He also presented the statistical combined cell model to predict the failure properties of short fibers reinforced composites

Finally the suggested Finite element approach is used in the simulation of a rigid coupling. The simulation loading and boundary conditions are performed based on Rivin guidelines for power transmission coupling design **[29]**. The results are compared with the conventional isotropic simulation results. The isotropic simulation assumes isotropic homogenous properties of the coupling material. The values of these isotropic homogenous properties are got from experimental testing results. The two results of the power transmission coupling simulation and compared to validate the suggested new technique of fibers composites simulation. Then the presented FEA model can be used for better optimization of products made from fibers reinforced composites with lower dependence on experimental investigations.

This chapter is a literature review for short fibers reinforced thermoplastics and thermosets. The technologies used in the processing of fibers reinforced polymers composites with injection molding and compression molding are reviewed. Fibers including both synthetic and natural are widely used as a reinforcement with both thermoplastic and thermoset polymers. Fibers enhance the mechanical and thermal properties of the polymeric composites. In this review we discuss the mathematical modeling and simulation techniques used in describing the relation between the composites and their constituents' mechanical and thermal relations. Different micromechanical models are reviewed.

Then, The use of natural fibers as a substitute to the conventional fibers like glass, aramid, and Kevlar are studied. The properties of the natural fibers reinforced thermoplastics and thermosets are compared with the synthetic fibers, and the applicability of the natural fibers polymeric composites are checked in specific applications.

The technological methods used in optimizing the use of short and long fibers usage with thermoplastics injection are also reviewed. A new technique where the long fibers are directly mixed with the thermoplastics resins after they exit the extruder nozzle is presented. The design and process parameters modifications to apply the new technique of direct long fibers mixing are introduced.

Rivin guidelines for rigid power transmission coupling are mentioned. These guidelines will be used in the design and simulation of the power transmission coupling manufactured from short fibers reinforced composites in the analysis of the studied research **[29]**.

2.2. Natural Fibers as a substitute to Synthetic fibers

Fibers are widely used as reinforcement constitute in polymeric composites. Synthetic fibers are used more than natural fibers due to their better mechanical properties. New researchers are studying the application of natural fibers as reinforcements to the thermoplastics injected and extruded products. New material sciences and technology approaches are followed to improve the specifications of the natural reinforced thermoplastics composites. In order to enhance the mechanical properties of natural fibers the following action can be done:

1. Due to the hydrophilic nature of nature fibers, a chemical treatment is required to increase the bonding quality between the fibers and matrix. **[30]**
2. Optimizing the fibers and fillers percentage
3. Optimizing the fibers loading percentage
4. Optimizing the selection of the processing techniques **[30]**

Recently, natural fibers have been studied widely as an alternative to the conventional synthetic fibers because of their availability, low cost, high specific strength and modulus, eco-friendly, biodegradability, recyclability, and non-abrasive specifications. **[30,31,32]**

In some natural fibers reinforced polymeric composites like the hemp, and Kenaf fibers showed a dramatically increase in the tensile strength, and Young's modulus by increasing the fiber loading percentage. **[30]**

Thermoplastics are more dominating as reinforcement with natural fibers. Matrices like PP, PE, and PVC are commonly used with natural fibers. **[30]**

2.2.1. Drawbacks of natural fibers reinforced thermoplastics

Natural Fibers have undesirable composites properties due to the low wetting or compatibility of the hydrophilic natural fibers and the hydrophobic thermoplastic matrices. It can be solved by employing chemical modifications to the surface of the natural fibers to enhance the adhesion between the matrix and fibers. **[30]**

The high temperature and shear stresses required in the thermoplastics processing is a significant source of natural and even high strength synthetic fibers damage. This may result in fiber length reduction in order of 10-100 times. This problem can tackled by decreasing the viscous flow effect of the thermoplastics, or by using innovative techniques in the fiber reinforced thermoplastics processing. **[33,34,35]**

2.2.2. Natural Fibers Surface treatment

According to the hydrophilic nature of the natural fibers, they have tendency to water and moisture absorption. This results in poor mechanical properties. In addition to the hydrophilic nature, natural fibers surfaces have waxes, and non –cellulosic substances as hemi-cellulose, lignin, and pectin. These substances results in poor adhesion between the fibers and the matrix of the composites. So, A chemical treatment to the fibers is required to improve its hydro-phicity and remove the undesired substances. Chemical treatment of the natural fibers will enhance their mechanical, wet ability, and roughness properties.