وزارة التعليم العالي
والبحث العلمي
جامعة ديالى
كلية الهندسة

التحقيق في مركب مصفوفة البوليمر الهجين على الخصائص الميكانيكية و قابلية التشغيل

رسالة مقدمة لمجلس كلية الهندسة جامعة ديالى حول استيفاء جزئي لشروط الحصول على درجة الماجستير في هندسة علوم المواد.

من قبل
نور حسن علي

بأشراف
أ.د. سهى كريم شهاب
أ.م.د. مزهر طه محمد

رجب ١٤٤٤هـ العراق كانون الثاني ٢٠٢٣م

Ministry of higher Education
And Scientific Research
University of Diyala
Collage of Engineering

Investigation of Hybrid Polymer Matrix Composite On the Mechanical Characterization and Machinability

A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for Master Degree in Materials Engineering Science.

by
Noor Hassan Ali

Supervisor by

Prof. Suha K. Shihab(Ph.D.)
Asst. Prof. Muzher T. Mohamed(Ph.D.)

2023 A.D Iraq 1444 A.H

CHAPTER ONE

INTRODUCTION

Chapter 1

1.1 Introduction

Polymer is an important material in engineering applications due to its low density, ease of manufacture, and low cost. By developing various types of polymers and their compounds and effectively using them in industrial applications, the mechanical and physical properties are improved [1]. Polymer matrix composites are more appealing than metallic materials due to their weight-to-size percentage, dependability, and low cost [2]. Hybrid polymer composite materials are fabricated by using more than two constituents, in which at least one is the matrix and others are fibers and fillers. Hybrid polymer composites are becoming increasingly popular in engineering applications due to their excellent mechanical qualities [3-5]. In addition, the manufacturing of hybrid polymer composite materials has increased in recent times and competition for obtaining the accurate shapes and dimensions. In turn, the advanced manufacturing process such as abrasive water jet process (AWJM) was resorted to and the interest of industry and researchers in it increased due to its usefulness [6].

1.2 Hybrid Polymer Composites

Hybrid polymer composites are composites with a polymer matrix reinforced with two or more different types of natural and synthetic reinforcements. The matrix can be made of either thermoset or thermoplastic polymer [7-9]. Thermoplastic it is one of the polymers that melts when heated, which allows it to be formed and reshaped. Thermoset it is one of the polymers that cannot be reformed after curing / polymerization. It is characterized by a high density of cross-linking, so it has superior properties, which are flexibility, high strength, durability, chemical and thermal resistance, but it has very little impact resistance. Among these refractory materials are polyester, epoxy resin, polyurethane and formaldehyde resins [10]. The reinforcements of polymer matrix are available in different forms including fibers (short fibers and long-fiber woven fabrics), particles, filaments, and flakes [11]. The properties of hybrid polymer materials vary depending on the reinforcements used and the way it combines with the matrix, and the reinforcement content. When reinforcements are used, hybrids have an advantage because they complement each other, balancing performance and cost [12]. Figure 1.1 shows the classification and form of the hybrid [13,14]:

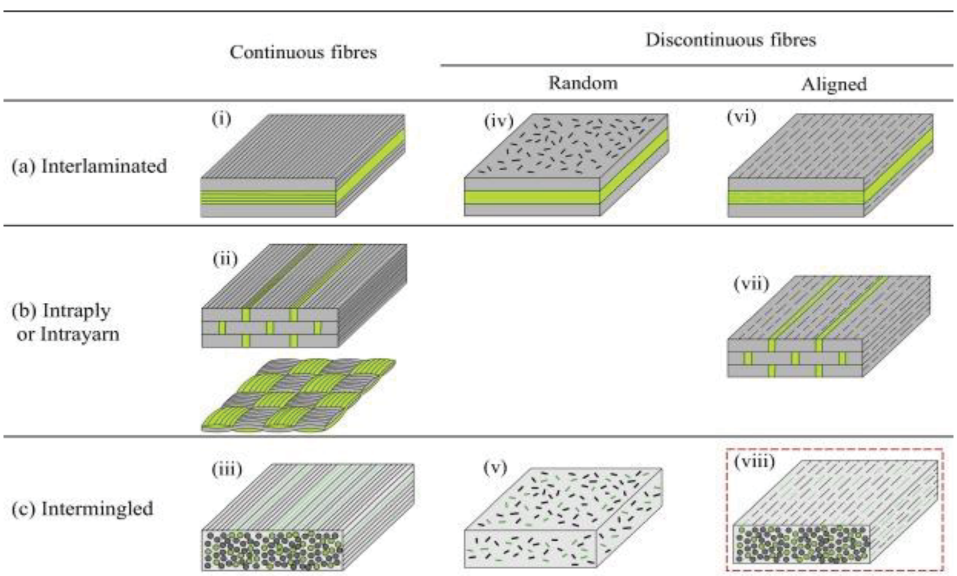

Figure 1.1 Classification of hybrid form of continuous and discontinuous fiber [13].

Some special properties of hybrid polymer composites [8,15,16]:

- Superior strength-to-weight ratio.
- low cost and simplicity of manufacturing processes.
- Excellent chemical resistance.
- Excellent performance.

- Hardness.
- Good mechanical and physical properties.
- Insulating properties.
- Best thermal and electrical properties.

1.3 Applications of Selected Hybrid Polymer Composites

The demand for hybrid polymer composites is currently increasing due to their distinct characteristics, which include high strength to weight, hardness, chemical resistance, high quality, low cost, and others. Researchers, technicians, and the market have shown an interest in hybrid polymer composites, particularly those reinforced with fibers and particles, The applications of selected hybrid polymer composites in this research include automobiles parts (wheel and rims, body panels, floor, roof and underbody structures), engineering, structural components of aircraft (fuselages and wings), and electronic components such as in printed circuit boards [17], laptops, desktop computers, cell phones, printers, fans, coolers, air conditioners, watches, thermal conductive, electrical insulation and packaging [8,10,15,16].

1.4 Carbon Fiber Reinforced Polymer Composites

There are two types of fibers, which are natural fibers, including (pineapple fibers, banana fibers, flax fibers, jute fibers, etc.), and the other are synthetic fibers, including (carbon fibers, glass fibers, aramid fibers, basalt fibers, boron fibers) [11]. Carbon fibers (CF) are among the most popular and widely used fibers due to their excellent mechanical properties, strength-to-weight ratio, thermal and chemical properties [18]. The continuous fibers carry mechanical loads support the matrix and providing the ductility and durability, protecting the matrix from environmental damage or damage during transportation. Due to its superior performance, continuous fibers are often used in polyester or epoxy resin matrix [19]. Carbon fiber reinforced polymers (CFRP) are composite materials reinforced with CF that have high strength and rigidity on the basis of the polymer matrix. Because these composite materials are synthetic, their performance and properties can be tailored to the application by adjusting their direction, length, strength, and quantity [20]. Therefore, they are used in a variety of applications, including structural components in concrete, aerospace, ships, cars, and other transportation industries [21,22]. CF are anisotropic (transversely isotropic) which are thin strands of diameter (5-10μm) visible to the human eye, are compared to the size of a human hair as shown in Figure 1.2, which contains at least 90 w% carbon. It can be made from polymer feedstock, such as polyacrylonitrile (PAN), cellulose, pitch, and polyvinyl chloride through heating and tensile processing [23,24]. CF have excellent tensile strength, stiffness, creep resistance, chemical stabilities in the absence of oxidizing agents and good thermal and electrical conductivities but have low impact strength and a tendency to brittleness. Due to its characteristics, CF applications have recently expanded to include aviation, automotive, military, turbine blades, construction, lightweight cylinders and pressure vessels, marine, medical, and sporting goods [25,24].

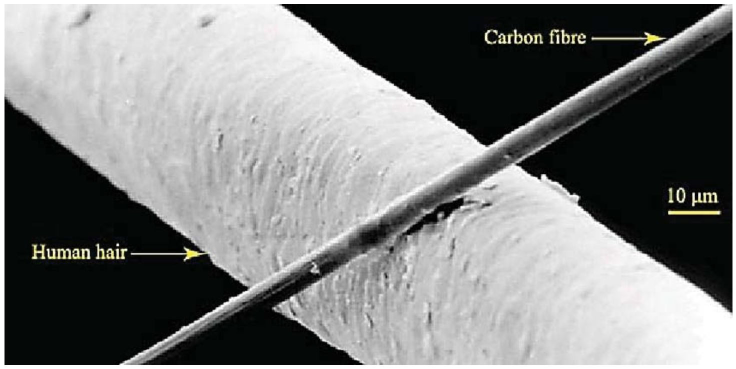

Figure 1.2 Comparing human hair with carbon fiber [23].

1.5 Ceramic Particles Reinforced Polymer Composites

The particles reinforced polymer composites are in different geometric shapes such as spherical, tubes of random shape, where they vary in size, ranging from nano to micro [11]. The properties of the polymer depend on the size, content and shape of the ceramic particles [26-28]. Ceramic particles have high hardness, modulus of flexibility, and abundance in nature. Consequently, the ceramic particles reinforced polymers (CPRP) possess good mechanical and physical properties like high ductility and adaptability, excellent thermal conductivity, high strength, and low cost [26,27]. The two classes of materials i.e. Polymers and ceramic particles are frequently combined to create composite materials that complement each other's thermal and mechanical properties.

The most commonly used ceramic particles as reinforcements within a polymer matrix are Silicon carbide (SiC), Alumina (Al_2O_3), Titanium dioxide (TiO_2), Copper oxide (CuO), Zinc oxide (ZnO), Silica (SiO_2), zirconia (ZrO_2), Aluminum nitride (AlN), Boron nitride (BN) [26,28]. Particulate ceramic reinforced polymer is an important material in many industrial applications, as well and other technologies such as abrasives, chemical catalysts, electronics and refractories, medical industry, and protective equipment [29].

Silicon carbide is a super- propellant filler of low weight and high durability that nominate it to improve the mechanical and environmental properties of the part [30,31]. Alumina has high strength, and hardness, as well as excellent corrosion and acid resistance and thermal conductivity. Therefore, these two types i.e. silicon carbide and alumina are used as a reinforcement within polymer matrices in a variety of applications including automotive, electronic insulators, substrates, and corrosion-resistant components [29].

1.6 An Overview of Hand Lay-up Process

Manufacturing processes of polymer matrix composite are classified based on the type of polymer due to differences in physical and chemical properties, which are affected by reinforcement type, relative volume fraction, stacking sequence, stacking direction, and layer number [32].

Hand lay-up, also known as wet lay-up, is a polymer composite manufacture technique in which the resin and reinforcement are manually applied to prepare the laminated composite structure. It is the most basic, simplest, and widely used method of producing polymer matrix composites (PMCs) [10,33]. The most important applications of the hand lay-up process are the automotive and truck body components, wind turbine blades, airframe components, tanks, swimming pools, and hulls for leisure boats [10]. Figure 1.3 shows the schematic of the hand lay-up process.

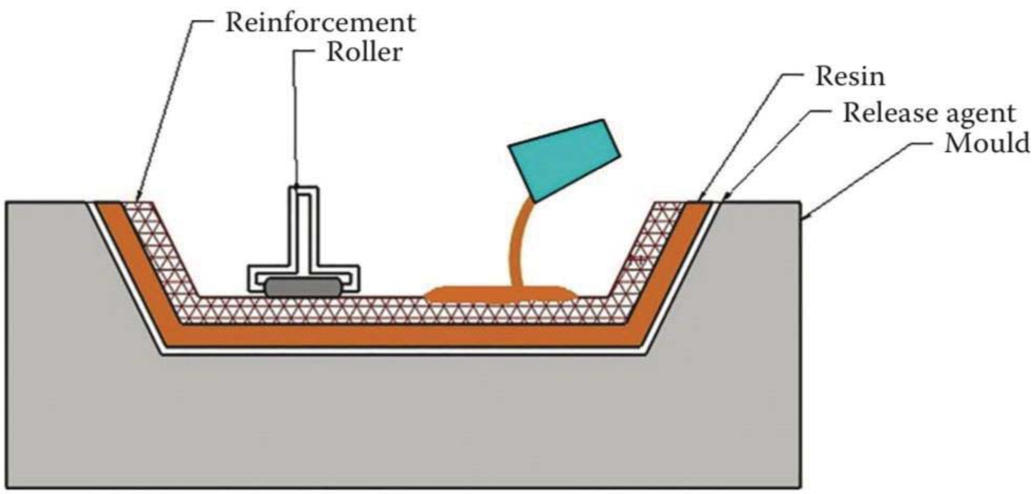

Figure 1.3 Schematic of the hand lay-up process [33].

The advantages of hand lay-up process include the following [33]:

- Simple procedure.
- Cost-effective operation with low equipment costs.
- The template design is simple to change, and there is virtually no limit to the portion size that can be produced.

Disadvantages of hand lay-up process:

- A highly skilled operator is required.
- This technique is only appropriate for thermoset (UPE, polyurethane, phenolic, vinyl ester, PLA, and epoxy).
- Time-consuming.
- The use of resin is hazardous to one's health.

1.7 Machinability of Polymer Composites

Machinability is the ease or difficulty in machining the materials that can be machined. It also evaluates the reaction of materials to the automatic system, which includes the workpiece and cutting tool, machine operation, and machining conditions. As a result, in the available conditions, it is difficult to obtain quantitative measurements and to adapt the mechanism to a wide range of formulas. Surface finish in terms of surface roughness is one of the criteria that has been used to assess machinability. The achievable tolerance and machined surface hardness and also characteristics of machinability [34], The reinforcement volume fraction, form, and orientation have a significant affect the machinability of the polymer when used as reinforcement [35].

Polymer composites are machined using conventional or nonconventional material removal methods. Conventional polymer composites machining is difficult and complex, particularly for low-thickness and heat-sensitive materials, due to some of the drawbacks such as (i. direct contact between cutting tool and the work piece, causing damage to both the cutting tool (tool wear) and the work piece, ii. variable cutting forces cause composites damage, iii. Fiber pulling and resin breakdown cutting, vi. Heat-affected zone and poor construction quality) [36]. As a result, nonconventional methods were used, such as abrasive water jet machining (AWJM), ultrasonic machining (USM), laser machining (LM), etc. because they are distinguished by many characteristics such as high precision, no burrs, high surface quality, there are no job-related tool requirements, have a high specific energy and more environmentally friendly methods. Figure 1.4 shows a diagram of nonconventional methods used for polymer composites machining [37,38].

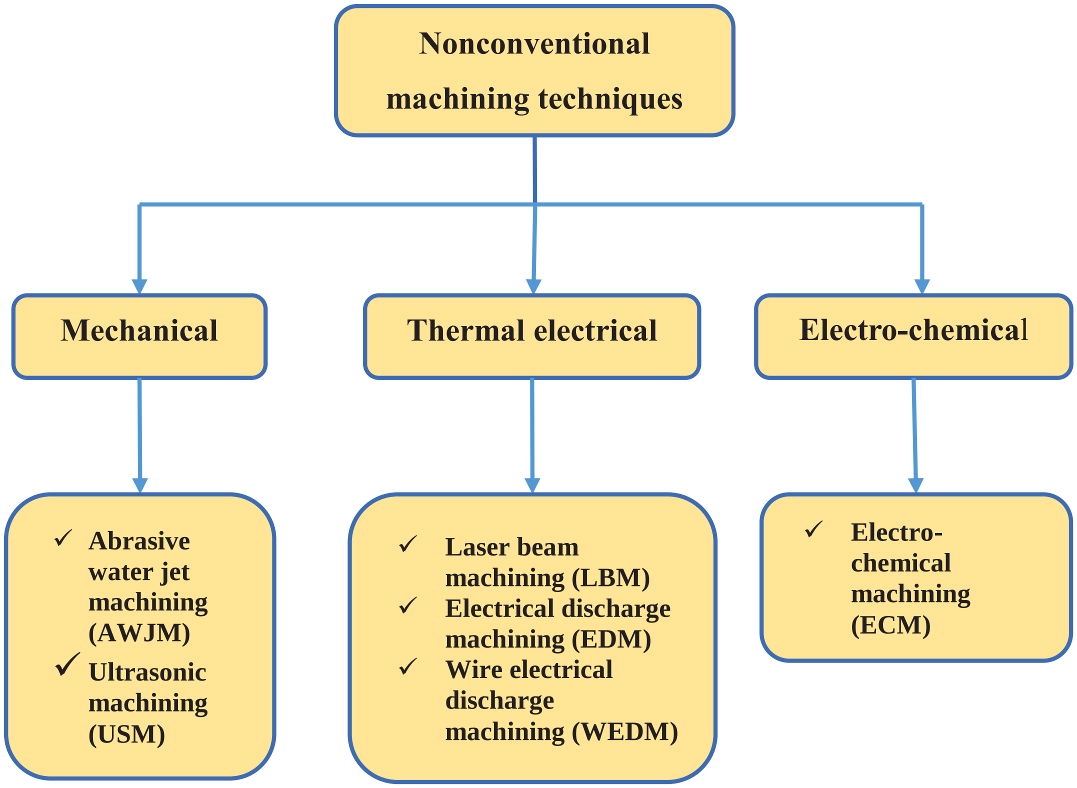

Figure 1.4 Nonconventional machining methods for polymer composites martials [32].

Nonconventional machining processes such as electrochemical process, threaten the environment while laser and plasma process produce a heat-affected zone which leads to large heat generation, matrix damage, weakness and inability to transfer loads. Further, electrostatic process such as electric discharge machining (EDM) includes high-cost electrodes and electrodes cause many problems. So, it is preferable to use abrasive water jet process because it is economical, high-precision, and suitable for brittle and hard materials, but it comprises drawback (noise) during process stream lag, cone, and taper effect and the abrasive water jet deflects as it enters into the workpiece [39,40].

1.7.1 Design of Experiment Based on Taguchi Method

Experimental design is a high-performance method. It is a statistical approach for many variables with a different number of levels using the orthogonal design that was developed into the Taguchi design. Scientists, technicians and engineers used the experimental design to facilitate and develop product design, as cost and time are reduced, which are among the most important factors affecting manufacturing process to perform experiments. Taguchi design was introduced, which is an easy, economical, and effective way to perform experiments because it requires a minimum number of experiments and their results are linked to levels of statistical confidence and improvement in product efficiency. This technology uses the concept of signal-to-noise ratio (S/N) to determine product quality characteristics and evaluate the results. The concept of signals is an indicator of how the response diverges compared to the objective value under various noise cases [41-43].

1.7.2 ANOVA Analysis

Statistical analysis of variance, which can be shortened (ANOVA), is used to determine the percentage of the effect of factor changes, and then conclude whether these factors have a significant impact on the research outcome (responses), depending on the value of F (Statistic) and P (Probability) both known (variance percentage). At alpha level 5% (α=0.005) determines of this statistical importance i.e. the possibility of building the incorrect decision while the null hypothesis is proper [42,44,45].

1.7.3 Optimization

Optimization is used to get the most out of a limited set of experiences and is an important method for decision-making in industry challenges. Because quality characteristics are dependent on similar control parameters, the S/N ratio provides the quality characteristics [46].

1.7.3.1 Multi Optimization Using Grey Relational Analysis

The Taguchi design is a strong design to detect the single optimization trouble. Grey relational analysis (GRA) is a way to take complex problems that have multiple factors and responses and combine them into one goal to get the best alternative from multiple experiences. Therefore, when determining quality based on several attributes, Taguchi design gives each response a separate attribute, and looking at the attributes of each response may lead to wrong production of the overall performance, and it cannot be obtained the specific feature [46-49].

1.8 Outline of The Research

This thesis includes the following five chapters:

- Chapter one: Reveals an introduction to hybrid polymer materials and their synthsis method (hand lay-up) in addition to the unconventional machining processes used for hybrid polymer composites.
- Chapter two: Includes some literary reviews, research, and works on the subject of the thesis, such as research on the mechanical and physical properties of hybrid polymer composites, as well as machinability of hybrid polymer composites and research gap and objectives.
- Chapter three this chapter includes: Experimental work for the synthsis of hybrid polymer composites and an exploration of mechanical and physical tests, abrasive water jet machining process, design of experiment (DOE) by used Taguchi design.
- Chapter four: It discusses the results obtained through mechanical and physical tests, and machinability of hybrid polymer composites by AWJM based on design of experimental (DOE) by Taguchi design and obtaining the indivdual and muli optimal AWJM parameters by analysis of variance (ANOVA) for signal to noise ratio and grey rational grade that have been considered in this thesis.
- Chapter five: The summary of findings and limitations during the implementation of this action plan includes the thesis and recommendations for future work.

Abstract

Hybrid polymer composites have recently become the interest of the world and their uses are increasing in various applications, especially mechanical, electronic, and other applications. Recently, advanced machining techniques for hybrid polymer composites have been used to solve many problems during machining processes, including the ability to form complex shapes, high performance, better surface features, and high levels of accuracy. In this study, hybrid polymer composites consisting of an epoxy matrix and reinforced with six layers of carbon fibers with a fixed percentage (15%) and ceramic particles (SiC and Al_2O_3) with different weight percentage were prepared by hand lay-up method. Mechanical tests including (tensile test, flexural test, impact and hardness test) as well as physical tests, including (thermal conductivity test, and density calculation) were conducted. The results of mechanical tests showed that an improvement in the tensile and flexural properties was of (19.7%) in the tensile strength, (40%) in the modulus of elasticity, (55.26%) in the flexural strength and (69.49%) in the flexural modulus, (12%) in the hardness using hybrid polymer constituent A4 (70 wt% Epoxy+15 wt% CF +10 wt% Sic +5 wt% Al_2O_3) compared A1 free of ceramic particles. However, this hybrid polymer constituent includes lowest value of impact strength. The results of physical test reveals that the enhancement of thermal conductivity was 40% with maintaining the light weight of sample A4. Also, the morphological analysis indicated the uniform distribution of particles, the best defect-free surface and the bonding strength between the reinforcement and the epoxy matrix can be obtained using this constituent which has contributed to the improvement in the mechanical and physical properties. The AWJM automation process was also performed based on design of experiment (Taguchi L_{18} design) to study the effect of the selected AWJM parameters (the hybrid polymer constituents (A), transverse velocity (V), stand of distance (SOD)) on the different response variables (surface roughness, hardness, kerf width). The analysis of variance (ANOVA) concluded that the hybrid polymer with the constituents A4 to has the most influential factor on the responses followed by V, and then SOD. The contribution percentage for AWJM parameters (A, V and SOD) was (79.70524%, 12.33802%, 6.77049%) respectively. Moreover, the GRA was beneficially used to determine the multi optimization of AWJM parameters. The multi optimum results based on GRG showed that optimum AWJM parameters were ($A_4V_3SOD_3$) i.e. at hybrid polymer constituents ((70% wt Epoxy + 15% wt CF + 5% wt Al_2O_3 + 10% wt SiC), V at 300mm/min, and SOD at 6mm) to produce ideal machined surface. The confirmatory test was carried out to investigate the validity of the results and the obtained optimal combination of responses for the best machinability was the highest hardness (89.5 H) with the lowest values of surface roughness and kerf width (5.0205 μm) and (850.31 μm) respectively.