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AN OVERVIEW OF ADVANCED JOINING TECHNIQUES FOR POLYMER AND COMPOSITE MATERIALS

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Abstract: Products and structures made of polymers and composites require efficient and advanced material joining processes in modern structural engineering to achieve high quality and performance. Designers or engineers must think about and understand the various joining solutions available and how they can be improved with advanced technological processes. Understanding the advantages and disadvantages of each potential technique from the beginning of the project is critical. While this paper summarizes all joining methods, it focuses on the most recent advancements and recommendations on various welding techniques. The goal of this work is to provide up-to-date information as well as to describe promising solutions and techniques that have been developed and proposed for future work.

Key words: Adhesive bonding, Composites, Joining, Polymers, Processing techniques, Welding

1 INTRODUCTION

Polymer and polymer composite materials are well-known engineering materials that, due to their excellent combination of properties, are used in a wide range of important applications such as packaging, construction, equipment, electronic parts, automotive parts, mechatronics, bioengineering, energy, oil and gas, sports and leisure and aerospace. Their application far outnumbers that of any other material available due to the numerous benefits they provide, such as good toughness, high strength-to-weight ratio, non-corrosiveness, good chemical resistance, improved design flexibility, moisture resistance, low thermal and electrical conductivity, ease of fabrication into complex shapes [1]. Engineering polymers have excellent mechanical, thermal, optical, and chemical properties and improved workability [2]. Furthermore, the properties can be altered by incorporating various compounds, reinforcing agents, colorants, plasticizers,

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stabilizers, flame retardants, and other substances [1]. In general, composite materials are made up of at least two materials that do not dissolve or blend together but work together to provide properties that outperform the individual materials [3]. There are three distinct regions in composites: the matrix, the reinforcement, and the interface. Properties can be tailored to a specific need by selecting the right combination and the manufacturing process that brings these regions together. The matrix material can be any material, but the most common ones are ceramic, metal, or polymer. There are numerous polymer matrices encountered on the market, with thermosets and thermoplastic composites being the most common [4]. Table 1 lists some of the polymers and polymer composites used and their characteristics.

Table 1. Engineering polymers and polymer-based composites

Polymers and polymeric composites		**Characteristics and application**	**References**
Thermoset polymer	Epoxy (EP)	Resin as cohesive material in adhesive, great impact resistance, stiffness, durability	[2],[4]
Polymer composite	Carbon fiber-reinforced epoxy (CE)	Cohesion of fiber-reinforced composite, high inherent specific strength, excellent design flexibility, CE composites incorporate nanofillers	[2],[4],[5]
Polyurethane (PU)	Thermoplastic PU Flexible PU Rigid PU PUI Water-borne PU	Thermal insulator, flexible sealant rigid, flexible, thermoplastic, waterborne, binders, coating, adhesives, and elastomers. Used in industrial equipment, paints, liquid coatings, elastomers, rigid insulations, elastic fibers, flexible foams, integral skins.	[2],[4],[6]
Polyolefin plastic	Polyethylene (PE)	Excellent mechanical, processing properties, chemical stability, high ductility and impact strength, low friction, strong creep under persistent force, water repellent, good electrical insulator, good pressure and radiation resistance, non-toxic. Used in packaging, biomedical applications, production of film, pipes, anti-corrosive agents, electrical insulation.	[2],[4],[7]
Acrylic polymer	Acrylic	Strong, stiff, transparent, excellent fatigue endurance, impact resistance, good toughness. Used for lighting, electronics screen, automotive components, outdoor glazing in architecture, construction.	[2],[4],[8]
Thermoplastic	Naylon 6 (PA6) or Polyamide 6	Used in the automotive sector for moulded components, with a tensile strength of 81.4MPa, young's modulus 2.8 GPa	[2],[4]
Thermolastic polyamide	Naylon 66 (PA66)	Harder and stronger than nylon 6, high-quality general-purpose wear-resistant. Used in mechanical engineering, automotive and general machinery construction - plain bearings, coil bodies, guide and clutch parts, gears, cams, rollers, slide bearings, seal rings and guide rails	[2],[4],[9]

Composite PA6 + glass fiber	Polyamide 6 glass reinforced PA6 GF	Used in the automotive sector for high-strength and durable moulded components,	[2],[4]

Understanding the performance differences and joining capabilities of polymer and polymer composite materials can assist in product and sourcing decisions. Joining is an essential manufacturing technique that is constantly improving, especially in structural applications for the production of modern engineering products and structures. Many factors, including desired output, project budget, availability of machinery and equipment, and required joint quality, influence the decision to select the best joining solution for a specific application [3]. Joint performance is critical for ensuring compliance with the purpose as well as all applicable design codes and specifications. When selecting materials and overall design, it is important to consider the joining technique in order to facilitate the joining mechanism while maintaining structural performance and other design criteria [3]. Mechanical fastening, adhesive and solvent bonding, and welding are the three major methods for joining plastics and composites [5]. Furthermore, hybrid joining methods that combine these various techniques in a single joint are viable options [2]. A decision on joining process options is influenced by several factors, including material, joint configuration, connection strength, process cost, speed, and production quantity. Welding is an appropriate process for thermoplastic polymers and composites because heat can melt the connecting interface, resulting in a weld after cooling. On the other hand, thermoset systems can be joined using adhesive bonding or mechanical fastening. Some methodologies are inapplicable due to the specifics of joint configurations and geometry, and alternative solutions, such as the use of hybrid processes, where multiple joining processes are used to achieve higher-performing joints and design, are required [2]. Plastic welding techniques are classified according to the nature of the heating source: techniques that use an external heat source, techniques that generate heat through mechanical movement, and techniques that use electromagnetism directly. Some of these techniques can be used for polymer composites but knowing that composites have their advanced properties from the reinforcement the weld will be the weak point.

This article describes good-joining practices for polymers and composites and the factors that influence the selection of the joining process. Adhesive bonding, mechanical joining, and some welding techniques are covered in detail, with an emphasis on the most recent advances in the field. Following the extensive literature review, future research and recommendations are proposed.

2 JOINING POSSIBILITIES OF POLYMERS AND COMPOSITES - METHODS OF MECHANICAL JOINING, ADHESIVE BONDING AND WELDING

The structural integrity is heavily reliant on the quality and durability of joints, which can be a weak point in the assembly. As a result, selecting an effective method of joining is critical for meeting functional requirements and ensuring structural stability. The forces that affect joints can be mechanical, physical and chemical and the joining processes can be classified as mechanical fastening, adhesive bonding and welding [1-3],[10]. There are numerous possibilities within each category and combinations of different joining processes that can be used concurrently, referred to as a hybrid joining process, which has demonstrated credibility in many cases. However, deciding on a joining solution for a specific application remains difficult. It entails making trade-off decisions between properties and priorities such as performance, cost, time, weight, and overall quality [3].

2.1 Mechanical fastening

Mechanical fastening of polymers and composites is a simple and low-cost technique that generates connection forces between two or more materials by using mechanical loads or auxiliary mechanical components. Mechanical joining employs fasteners such as screws, nuts, bolts, washers, rivets, and pins or with integrated design elements of snap-fit or press-fit joints [3][10]. When high-performance joints are required, mechanical fasteners can be difficult to use, but in most cases, they are the simplest and cheapest solution, especially when different types of materials are to be joined. The disadvantage of using this technique is that highly localized stresses can form around the fasteners, which can cause subsequent in-service corrosion and also it is not a leakproof technique. When used on soft and low-strength materials such as polymers and some polymer composites, damage is unavoidable. The holes required for fasteners cause micro and macro damage to the polymer and composites, making strength degradation difficult to avoid [3]. They can also increase the weight of the structure, which can be a disadvantage in some applications, such as aircraft. Fasteners can be metallic or nonmetallic, permanent or removable, depending on the structure's life expectancy and load capacity. The selection of joining fastener, joint configuration, geometric parameters, lay-up stacking sequence, clearance between fastener and hole, preload or initial clamping force all influence mechanical joint design [3]. This method of joining is widely used in electronics, aerospace, automotive, civil engineering, and mechanical construction. With proper designing and numerical modeling of mechanical fasteners, stress concentrations at joints can be determined [2]. Mechanical joining through attachment with no third body fastener is possible if the joined parts are designed to provide an interlocking connection that resists load through the joint [3]. However, in the case of composites, the complexity of moulding in the interlocking features can be difficult. Other mechanical attachment methods, such as cinching and clinching, are not generally applicable to composites [3].

2.2 Adhesive bonding

Adhesive bonding has proven to be an excellent joining strategy in structures with complex designs that also necessitate high-performance joints. The field's development has been very rapid in recent years, particularly with numerical methods that researchers have investigated in order to predict the stress fields' dependency on geometry and analyze the performance of joints [2]. It can be used to join various materials, but in many cases, one of the materials that must be bonded is polymer or polymer composite. In this joining process, the adhesive is applied to the interface that is intended to be connected, and depending on the type of adhesive, a solid connection is obtained after melting or polymerizing. In order to attain high quality, the joint is pressed together. Although the established adhesive joint is completely leak-proof and can be done with various materials and shapes, it is not suitable for high-volume production due to the high material cost and long curing time [1]. Adhesives can be polymers with low surface energy, resulting in weak adhesion; this is why surface treatments are required. The passive surface treatment changes the surface properties, whereas the active surface treatment changes the chemistry, but both increase the surface energy [2].

With adhesive bonding, composites can be produced by adhering a resin (thermoplastic or thermoset) to structural fibers, but by definition, adhesive bonding should be considered a surface-driven process in which stresses and strains are transferred across an interface that connects two planes: the substrate and the adhesive. If the adhesive bond is less than 100μm thick, it is considered to be a single interphase between the surfaces, however, if it is thicker, it is treated as a separate component, with the joint described as a sandwich of two substrates, two interphases, and a layer of adhesive [3]. Load transfer in composites can cause failure outside of the adhesive/interface region due to z-direction adhesion between fiber layers, making the resin the weakest point [3]. The adhesive joints are sensitive to cleavage forces and small peel loads, therefore it is recommended that the joint design should be in such a manner that the adhesives are loaded in compression and shear. When connecting sheet materials, the load-carrying capacity of a joint does not increase gradually with the joint area because maximum stress at the leading and trailing edges of the joint limits the load-carrying ability. Examples of adhesive joint configurations are shown in figure1.

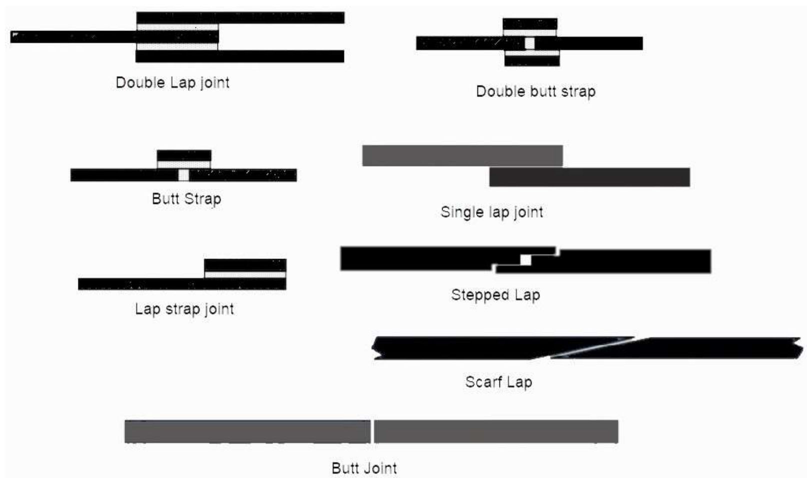

Figure 1. *Various simple adhesive joint configurations*

Today, numerical methods in the design process can be used to determine the best geometry and materials that can withstand loading and working conditions. Any potential fractures or damages in the adhesive joint can be revealed by the analysis. The numerical modeling techniques are appropriate for determining the influence of geometrical parameters because they have been validated through experimental work. The interaction between the mechanical behavior of the substrate and the adhesive is the most important factor influencing joint performance when polymeric or composite substrates are used [2]. Even though adhesive bonding performs better under fatigue load, there are still dangers of fatigue failure that need to be investigated experimentally and numerically. It can be concluded that it is a useful technique for a wide range of applications, particularly when joining polymers or composites. To achieve good joint quality, special attention should be paid to surface treatments of polymer materials, as well as proper joint design and numerical analysis. In addition, when designing joints with adhesive bonding, one should consider the joint's working conditions, such as high humidity environments and fatigue loads[2]. When additional support is required, hybrid joints are an excellent choice, especially if peel or cleavage forces are present. Although the adhesive is a secondary joining component, it contributes to the connection's overall stability. Adhesive bonding may appear to be a great solution for joining polymers and composites, but some considerations must be made before making a final decision. The joints cannot be easily disassembled with additive joining, and elevated temperatures and specialized fixtures may be required. High-strength adhesives have poor properties, are brittle, and are sensitive to oil and moisture. Surface preparation and cleanliness are also important for consistent results, and thermal residual stresses can be induced [10][14].

2.3 Welding

Polymers and composites can be joined using a variety of welding techniques. Polymer welding, also known as fusion bonding, involves the application of heat to the contacting interfaces in order to melt the polymer, and after cooling, a solid joint is formed through intermolecular diffusion and polymeric chain entanglement processes. Thermoplastic composites can be melted and reshaped, so they can be welded. Thermoset matrix composites, on the other hand, can be joined with welding but only if the interface is a thermoplastic layer that can be melted, forming the joint that will hold the two parts together. Welding processes are classified into three types based on the energy source used to generate heat: electromagnetic heating, mechanical heating, and externally heated techniques[3][8]. The welding processes can also be categorized according to frictional heating, electromagnetic heating, bulk heating, and heating with thermal techniques [14]. There are various welding technologies that can be used in various situations, each with advantages and disadvantages that make them more or less suitable for a specific application.

Friction stir welding (FSW) is a joining process that is in a solid state, with minimum energy applied on the joining surface that is generated by the vibration or friction of a metallic pin. The generated heat melts the components that are aligned and pressured towards each other and after cooling they form a joint. A solid connection is achieved because the energy released by friction in combination with the pressure applied softens the base material without melting. This increases the activation energy between the surfaces causing plastic deformation and the joint is formed through the forging process. FSW of thermoset polymer is impossible because the materials will degrade, but thermoplastics can be welded with FSW with vibration, rotary friction, ultrasonic and orbital welding. In general, all of the challenges that come during welding are mostly the parameters and other manufacturing characteristics. The rotation of the pin will influence the area of heat affected zone (HAZ), and the faster rotation will result in a wider zone [10][12]. Other design parameters like feed speed and tooth depth will influence the mechanical properties of the joint [2]. This joining process is used in the automotive industry because the trend is toward lighter, safer, less expensive, and more environmentally friendly vehicles and reinforced polymer composites are a promising material that can be a good substitute for the formerly used steel and cast iron. Polymers such as polyethylene (PE), polypropylene (PP), polycarbonate (PC), polystyrene (PS), polyamide (PA), polymethyl methacrylate (PMMA), and other thermoplastics, as well as nanocomposites, can be successfully welded using the FSW process [12]. FSW is a quick and simple method of joining thermoplastic polymers and composites. Nevertheless, the effectiveness of this method is heavily dependent on the welding parameters. By analyzing the stresses and thermal gradients generated, finite element analysis can be used to optimize parameters.

Resistance welding involves the heating of an electrically conductive implant that is placed between two parts to be joined. The heat in the implant is generated thanks to the electrical resistance while passing a high electric current through the piece. With this generated heat, the surrounding thermoplastic softens and melts, and the welded joint forms after it cools down under adequate pressure. The contact between the surfaces and molecular diffusion is ensured with pressure [14]. The implants are electrically conductive materials (metallic) in different forms and shapes (wire or mesh form) or they can be unidirectional carbon fiber strips [3]. In general, the electric current used is DC or low-frequency AC, but there is a new variation of the technique that uses electrical current in the form of intense pulses (high energy impulses with pauses), called impulsive resistance welding (IRW). It uses less energy to melt the matrix and removes the overheating and delamination problems of the welded surfaces. The weld quality can be enhanced if the correct amount of energy and thermal insulation are used [3]. This technique is considered to be fast, simple, and applicable to large structures, for joining of carbon-fiber reinforced composites and thermoplastics except for the parts where there is heavy carbon loading or non-insulated components are used. There are also some common problems with this joining process, like uneven heating and the possibility of fiber movements [14]. There are other welding processes that fall under the electromagnetic heat group, like induction, microwave welding, and dielectric welding that are also suitable for the welding of polymers and thermoplastic composites.

The third category is thermal welding, which involves heating the two parts at the contacting surfaces to cause a decrease in viscosity, then pressing the parts together and slowly cooling down below the glass temperature to form a solid connection between the parts [14]. Under this category fall hot plate, hot gas, radiant, infrared, and laser welding. For a variety of reasons, *laser welding* stands out. For starters, it is capable of producing highly accurate and strong joints with tighter tolerances [1]. This is also possible with electron beam welding, but it would be more expensive due to the complexities of the equipment and setup [1]. The procedure involves bringing the two parts into contact, after which the laser beam heats up the absorbing material, which then heats up the translucent material via conduction. It is critical that one of the two materials is transparent enough to allow laser radiation to pass through while the other is absorbent enough. Weld quality is determined by laser characteristics, welding time, and material type [14].

3 CONCLUSIONS

This article examines several joining strategies for producing higher-quality joints when polymers or composites are used as basic materials in production. However, joint quality is a subjective term, and in order to accurately analyze it, specific analysis for the specific applications must be performed. According to the findings of this review, adhesive bonding, mechanical joining, and welding processes such as FSW and laser welding are already in use in a variety of advanced technological applications. The joints are strong and free of defects, but their potential can be increased by further optimizing the process parameters. Future research and development should focus on a broader range of materials in order to investigate the capabilities of joining various materials. Hybrid joints are a promising solution for improving the properties of specific joint designs. Combining techniques like FSW and laser welding, or laser welding and mechanical joining has the potential to reduce energy consumption. Other advantages may also emerge, such as the ability to obtain stronger joints for various materials and complex designs.

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