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Research Article

Welding Methods of Polymer Composites

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Abstract – Mechanical fasteners, adhesives and welding processes are used to join polymer composites. Although the mechanical joining process is carried out quickly, sealing cannot be achieved due to the holes drilled in the parts and high local stresses occur near these holes. A better stress distribution can be achieved with adhesive bonding, but they are difficult to apply and the processing time is long. Besides, adhesive selection and preparation and surface cleaning are vital for the strength of the joint in adhesive connections. When it is desired to obtain values close to the mechanical properties of the base material, welding comes to the fore. Furthermore, the processing times are short and it is also possible to provide sealing. Since welding of polymer-based materials is mostly carried out using heat, especially thermoplastic polymers can be welded. Thermoplastic materials can be softened and hardened repeatedly by heat, whereas thermoset polymers cannot be softened by reheating once hardened and therefore cannot be welded using heat. In this study, traditional fusion welding methods used in welding polymer composites and a new welding method that does not use heat are explained.

Keywords – Welding, Polymer Composite, Fusion Welding of Polymer, Thermoplastic Welding, Ultrasonic Welding

I. INTRODUCTION

Joining processes of polymer composites are divided into three main categories: welding, bonding and mechanical fixing [1], [2.]. The fact that mechanical fixing processes increase the stress concentration due to holes in the parts, the risk of galvanic corrosion and the increase in the weight of the connection limits the use of these methods [3], [2.]. Adhesive joints have relatively lower strength and, in some cases, the curing process of adhesives takes a long time [4].

Welding is one of the most important solution methods in cases where complex-shaped polymer composite materials cannot be produced with a single molding process and multiple parts need to be combined into a single piece [5-7]. Welding is an economical joining method for polymer composites, especially in cases where large amounts of joints are produced. Because there is no need for filler material in the welding of polymer materials, stress concentrations can be reduced, the welded connection type has higher strength than the other joining methods and the welding process can be applied much faster.

Polymer composites have a wide range of uses in many industries, especially automotive and aerospace, due to their low weight and cost. These composites, depending on the matrix material, are divided into two groups as thermoplastic and thermoset composites,.

Thermoplastics can soften again after each heating process and then harden again. Therefore, it is possible to weld these composites using heat. Additionally, different types of thermoplastics can be welded, provided that they are miscible with each other. In contrast, Thermosets solidify after a liquid-solid transition called curing and cannot be re-melted or softened after the curing process is completed [8]. For this reason, it is not possible to weld thermoset composites using heat.

There are approximately twenty different methods for welding polymer composites, all of which, except solvent welding, use heat energy for joining.. In methods using thermal energy, heat is produced in three different ways and can be divided into three groups: using an external heat source, producing heat by mechanical movement, and using electromagnetism. All these methods involve heating and melting the composite surfaces to create a bond. For this reason, welding is especially applied to thermoplastic and thermoplastic compounds.

II. WELDING METHODS FOR POLYMER COMPOSITES

The choice of welding method depends on several factors, including the type of polymer composite, the intended application, and the required strength and quality of the joint. Each method has its advantages and limitations, and it is essential to select the most suitable one for your specific needs. Additionally, proper surface preparation and joint design are critical to achieving successful welds in polymer composites. Depending on the welding process and the size of the parts, welding time varies from one second to several minutes.

Plastic welding processes can be divided into three groups: a) Processes involving mechanical movement – ultrasonic welding, friction welding, vibration welding, friction stir welding b) Processes involving external heating – hot plate welding, hot gas welding, Laser welding and resistive/implant welding. c) Processes involving chemical reaction: solvent welding.

A. *Ultrasonic Welding*

Ultrasonic welding is one of the most preferred methods in welding plastic materials. [9]. Ultrasonic welding uses high-frequency and low-amplitude mechanical vibrations to generate heat at the joint interface, melting the polymer matrix and forming a bond. When two parts are pressed together during the welding process, they cannot fully contact at the interface due to surface roughness, which causes contact asperities. Under dynamic vibration, it causes some of the mechanical vibration to dissipate in the form of heat and the overlapping asperities undergo deformation. The molten surfaces approach each other under pressure, and after the vibration is stopped due to compression flow, intermolecular diffusion, and entanglement of polymer macromolecules, the joint cools under pressure and solidifies. Because surface roughness can vary between parts, a roughness, usually a triangular protrusion is molded onto the upper parts to increase repeatability. Figure 1. Under cyclic loading, the protrusion called the energy director or concentrator undergoes the greatest deformation resulting in preferential heating, melting and flow to weld the parts together [10].

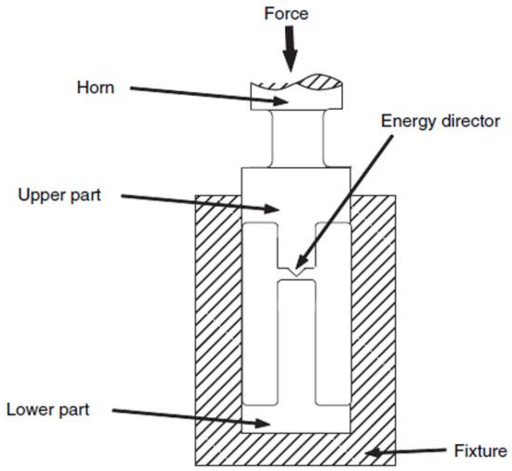


Figure 1. Parts for ultrasonic welding with triangle energy director

Ultrasonic welding is especially used for joining thermoplastics composites like automotive parts and medical devices because it is fast (typical cycle time ranges from a fraction of a second to several seconds), is easily automated, and the equipment is relatively inexpensive. Typical operating frequencies are between 10 and 75 kHz, but 20 kHz is the most common operating frequency and vibration amplitude is between 0.1 and 100 µm [11].

B. *Friction/Vibration Welding*

Friction welding involves rubbing the two polymer composite parts together to generate heat through friction. This method is suitable for both thermoplastic and thermosetting composites. In this method, friction is used to produce the heat at the interface to melt the material at the interface of the parts.

With the applied pressure, the molten materials flow together and form a weld at this interface after cooling. In this method, welding time can be carried out in short processing times between 8-15 seconds and can be applied to thermoplastic parts with planar or slightly curved surfaces.

There are three different friction welding applications: linear, orbital and spin. In the linear welding process, heat is generated by the friction that occurs with back-and-forth movements (Figure 2a).

In spin welding, parts are welded along circular mating surfaces. In this process, while one of the parts is fixed, the other is rotated against the fixed part until melting occurs under a certain angular speed and axial pressure (Figure 2b) [12]. In orbital friction welding, one part is rubbed relative to another in an orbital motion under axial pressure (Figure 3). Unlike linear vibration welding, the relative motion of the two parts at the interface is the same at all points around the perimeter, and constantly changes from transverse motion to longitudinal motion. In the orbital welding method, the upper part to be joined is vibrated by moving it circularly in all directions, thus generating heat and melting the polymer parts [13]. Vibration welding is similar to ultrasonic welding but uses lower frequencies. It is effective for joining large or complex-shaped polymer composite parts.

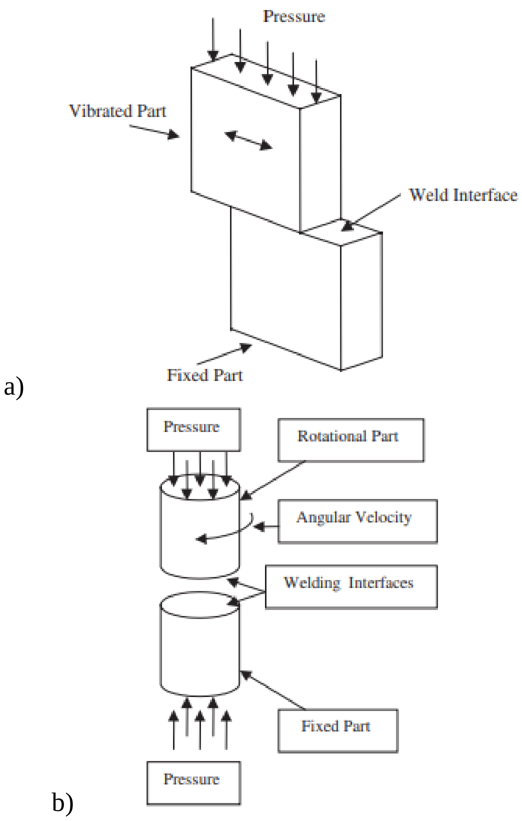


Figure 2. Schematic of a) linear vibration welding and b) spin welding [12]

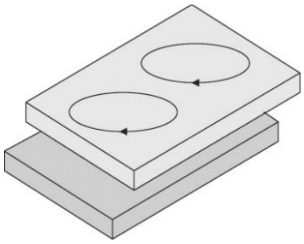


Figure 3. Movement of the orbital vibration welding [13]

The important process parameters in the process are vibration amplitude and frequency, welding pressure and welding time, all of which affect the strength of the resulting weld [12].

The vibration welding process consists of four stages (Figure 4):

In phase I: Solid friction phase, heat generated through friction raises the temperature of the interfacial area to the glass transition temperature of amorphous thermoplastics or the melting point of semi-crystalline plastics.

In phase II: Instationary melt friction phase, the material at the interface begins to melt and flows in a lateral direction, causing an increase in weld displacement.

In phase III: Quasi-stationary melt friction phase, the melt formation rate is equal to the melt displacement rate, so it increases linearly with time. At the end of Phase III the vibration motion is stopped and in Phase IV: Dynamic cooling phase/ Static cooling phase, the weld penetration increases slightly as the molten film solidifies under pressure [13].

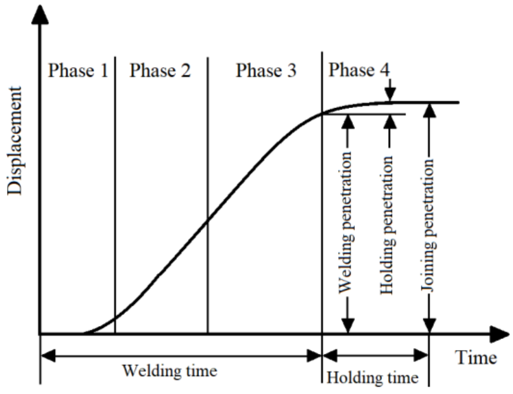


Figure 4. Displacement-time curve at the vibration welding.

Most of the vibration welding machines operate at weld frequencies of 100–240 Hz, the amplitude of vibration is usually less than 5 mm (0.2 inches), weld time ranges from 1 to 10 seconds (typically 1–3 seconds), with solidification times, after vibratory motion has ceased, of usually 4–10 seconds. Total cycle times typically range from 6 to 15 seconds resulting in 4–10 cycles per minute [13].

C. *Hot Plate Welding*

Hot plate welding is a commonly used method for joining polymer composites. The process uses a heated metal plate, also known as hot plate, hot tool, heaten plate, etc., is a technique commonly used to join injection molded components or extruded profiles [14, 15]. This welding technique is particularly suitable for thermoplastic materials, which can soften and melt when heated and solidify when cooled. Hot plate welding involves heating the joining surfaces of polymer composites using a heated plate. When the material at the interfaces begins to melt or soften, the hot plate is removed and bonding is achieved with the applied pressure. An axial load is applied to the parts during the welding process's heating and cooling phases.

Hot plate welding is performed in two ways, which are welding by pressure and welding by motion [16, 17].

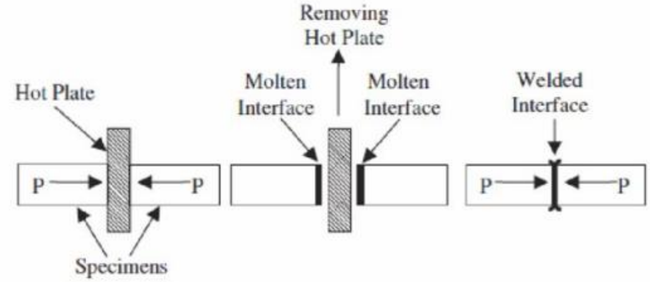


Figure 5. Schematic representation of hot tool welding [17].

In heated tool welding, parts are first brought into contact with the hot tool and a relatively high pressure is used to ensure complete fusion of the part and tool surfaces. Heat is transferred from the hot tool to the parts and a local temperature increases. Once the melting temperature is reached, the material begins to flow. This melting eliminates surface defects, curvatures and depressions at the joint interface and creates a smooth surface. Due to the applied pressure, some of the molten material comes out from the joint surface. At this stage, the melt pressure is reduced, more heat is given to the material and the molten layer thickness is increased. When sufficient melt thickness is reached, the pressure and surface temperature are reduced and the hot tool is removed between the parts. Then, the parts are brought into contact with each other and pressure is applied. During this time, intermolecular diffusion enables the formation of polymeric chains that determine the connection strength. As cooling and solidification occur, some of the molten material flows out from the sides due to the pressure applied. The pressure is kept constant during cooling to prevent distortion as the final molecular structure and residual stresses are formed during cooling [16].

In pressure heated welding, the hot tool is placed between the parts to be joined and pressure is applied directly, while in distance heated tool welding, also called displacement-controlled welding, mechanical stoppers or fixtures are used to control the welding process and part dimensions.

D. *Hot Gas Welding*

In this welding process, a heated gas is used to soften the plastics. For this reason, the technique is also called the hot air technique. In this method, the welding rod and the welding groove are simultaneously heated by a stream of hot gas until they soften enough to fuse; and then the welding rod is pressed into the welding groove. Figure 6 shows the schematic principle of hot gas welding.

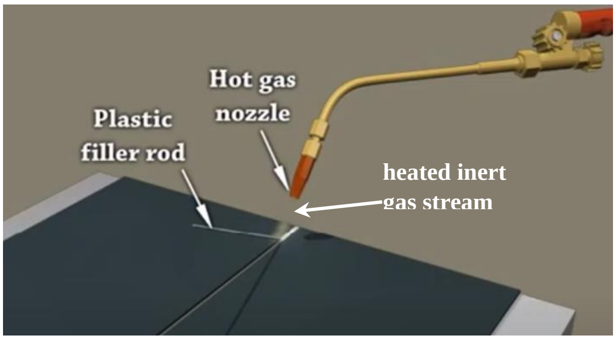


Figure 6. Principle of the hot gas welding [18]

A torch with an electrical heater to heat the compressed inert gas is used to soften the polymeric materials. The torch directs a stream of hot air toward the filler and the connection area [19]. A filler rod of similar composition to the polymer being incorporated is slowly pushed into the gap between the substrates (Figure 1). Although the filler rod is generally round in cross-section, oval, triangular, and rectangular cross-sections are also available [5].

Control of gas purity is an important factor for the treatment of hot gas. gas source quality. Impurities and contaminations present in hot gas can cause thermo-oxidative degradation, resulting in reduced strength. Before welding, the joining surfaces must be cleaned by solvent cleaning or grinding. Important process parameters are gas temperature, gas flow and welding speed. Gas temperature is generally in the range of 200–600°C and gas flow rates are between 15 and 60 L/min. Welding speed depends mainly on the skills of the welder after the process is performed manually [18-20].

Table 1 shows the temperatures [19] of the different types of plastics. The melting temperature of PVC is not well defined due to the wide distribution in crystal particle size [8], resulting in a wide melting range.

Table 1. Welding temperatures of different types of plastic materials.

Plastics	Welding Temperatures (^{O}C)
Acrylonitrile Butadiene Styrene	350
Acrylic	350
Hard PVC	220-300
Hypalon	600
Polyethylene (Hard)	250-280
Polyethylene (Soft)	270-300
Polyisobutylene	600

Among the important advantages of hot gas welding is the ability to weld parts of all shapes and sizes, cheap equipment cost (initial investment), portable lightweight equipment and therefore ease of use. However, despite all these advantages, welding speeds are slower than other plastic welding techniques and the welding quality depends on the skill of the operator, which limits its usage areas [21].

E. *Laser welding*

Laser welding uses a laser beam to melt the plastic in the joining area. It is a technique suitable for joining sheets, films, molded thermoplastics and textiles. Lasers are well-suited to deliver controlled amounts of energy to a precise location due to the ease of controlling the available beam size (10 μm – 100 mm width) and the range of methods available for precise positioning and movement of the beam. There are two general forms of laser welding: direct laser welding and transmission laser welding [22].

Direct laser welding of polymer materials is a specialized welding technique that uses high-intensity laser beams to join two or more polymer composites without the need for additional apparatus. This process is particularly useful for thermoplastics, which can be melted and fused together using laser energy.

In direct laser welding, a focused laser beam is directed onto the polymer surfaces to be joined (Figure 7). The laser energy is absorbed by the polymer material, causing localized heating and melting. As the laser beam moves along the joint line, the molten polymer fuses together. Once the material cools and solidifies, a strong bond is formed.

The success of direct laser welding depends on the polymer's ability to absorb the laser energy. The polymer's absorption spectrum must match the laser wavelength for efficient energy conversion. Some polymers may require the addition of laser-absorbing additives or pigments to enhance absorption [23].

Laser sources of 2.0–10.6 μm wavelength are typically used. At 10.6 μm (CO2 laser), radiation is strongly absorbed by plastic surfaces, allowing high-speed joints to be made in thin films. [24, 25].

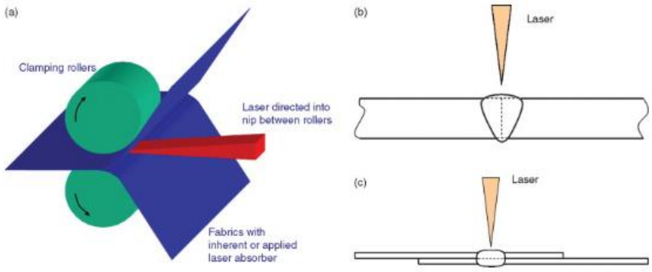


Figure 7. Direct laser welding formats: (a) welding into a nip between rollers, (b) butt welding, and (c) overlap film welding [22]

Transmission laser welding is used to join polymer materials by transmitting a laser beam through one of the materials being joined. This process is commonly used for transparent or semitransparent polymers, such as acrylics, PMMA (polymethyl methacrylate), PC (polycarbonate), and certain grades of PET (polyethylene terephthalate).

In transmission laser welding, a high-energy laser beam, usually in the near-infrared spectrum, is directed through one of the polymer components. The laser beam is absorbed by the mating surface of the second polymer component, causing localized melting and subsequent bonding as the materials cool.

The absorbing polymer component should be chosen carefully to ensure that it effectively absorbs the laser energy. Typically, additives or pigments are added to enhance the absorption of the laser energy [26].

The parts are positioned together before welding and the laser beam passes through the upper part to heat the joint at the absorbing surface of the lower part (Figure 8). The absorber in or on the lower plastic is typically carbon or an infrared/ultraviolet absorber with minimal visible color. Transmission laser welding is used to join thicker parts than direct welding, and since the heat-affected zone is confined to the joint region, there are no marks on the outer surfaces [22].

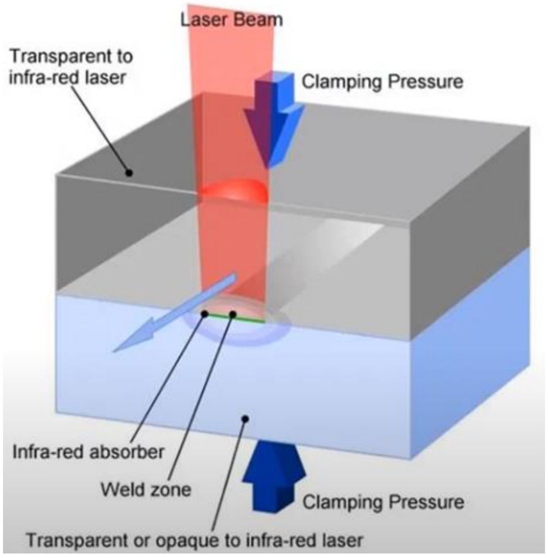


Figure 8. Schematic representation of Transmission laser welding process [26].

Proper joint design is crucial for successful transmission laser welding. The design should allow the laser beam to pass through one of the parts and be absorbed by the other, ensuring that the materials are brought into intimate contact for bonding.

Transmission laser welding is now widely used for joining thermoplastics in industry, using laser sources with wavelengths from 0.8–1.1 µm, such as diode, Nd:YAG, and fiber lasers.

The most important advantage of laser welding over other welding methods is the application of low amounts of heat to a limited area. Thus, high-strength joints and lower amounts of stress are obtained due to the low thermal effect (melting and solidification) on a smaller area. Moreover, since it is used with automation, it is also possible to weld complex-shaped parts. On the other hand, laser welding is very sensitive to the polymer material, processing history, pigmentation and additives. Laser welding is especially used for local and accurate welding of films, sheets or molded parts [27]. Laser welding has many advantages such as weld different polymer materials, minimal part stress, higher joint strength, lower joining cost and process monitoring.

F. *Induction Welding*

Induction welding of polymer materials is a specialized joining process that uses electromagnetic induction to heat and bond thermoplastic components. This technique is particularly useful for large or complex polymer parts, as it offers advantages such as energy efficiency and the absence of contact between the heating element and the materials being joined.

Induction welding relies on the principles of electromagnetic induction. A high-frequency (typically 2 – 10 MHz) alternating current (AC) is passed through a coil or induction coil, generating an alternating magnetic field [28, 29].

Induction welding is generally suitable for thermoplastic materials with conductive additives. Commonly used polymers include polyethylene (PE), polypropylene (PP), and thermoplastic olefins (TPOs). These materials often contain carbon black or metallic particles to enhance conductivity.

Induction welding, also called electromagnetic or EMF welding, uses induction heating an implant placed at the common interface of two parts being welded (Figure 9). This implant or seal is normally a composition of polymer to be welded with metal fibers or ferromagnetic particles. The heat generated melts and fuses the implant with the surrounding material. It is a reliable and fast technique that allows welding in less than a second for small parts and 30 to 60 seconds for large parts [30].

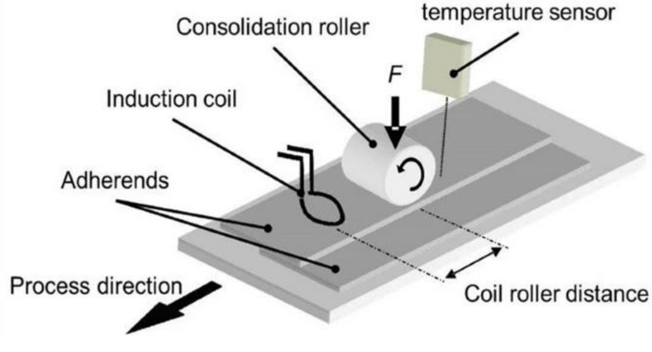


Figure 9. Process design and crucial components of the continuous induction welding process for thermoplastic composites [31]

When a polymer component with conductive additives (typically metallic or carbon-based) is placed in proximity to this coil, it experiences a phenomenon called Joule heating. The alternating magnetic field induces electrical currents within the conductive additives, and this results in localized heating at the interface of the two polymer components to be joined. As the polymer material softens and melts, pressure is applied to create a strong bond.

G. *Resistance welding*

Resistance welding of polymer composite materials is a technique used to join thermoplastic components by applying pressure and electrical resistance heating to create a strong bond. This process is commonly employed in industries such as automotive, electronics, and consumer goods.

Resistance welding is a method that allows rapid heating and melting of the polymer on the bonding surface by passing an electric current through a resistive heating element placed between the two plates to be welded (Figure 10). The heat generated in the resistance source is according to Joule's Law;

$$E= I^2. R.t.$$

where E= the heat generated (Jeule), I is the electric current passed through the heating element (A), R= the resistance of the heating element (ohm), and t= the time the current flows (seconds) [32].

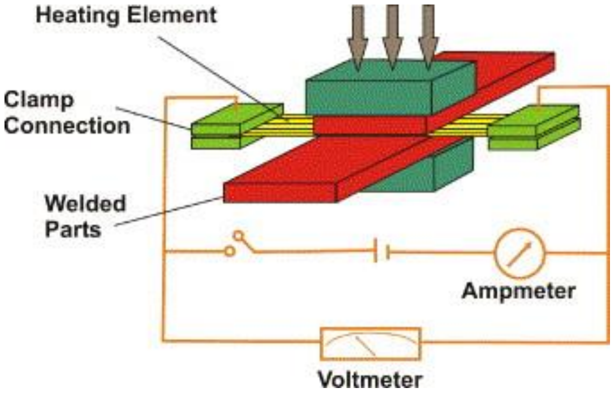


Figure 10. A typical experimental set-up of resistance welding [33].

Resistance welding is generally suitable for thermoplastic materials, including polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and others. The success of the process depends on the electrical resistivity of the polymer material. Resistance welding is used in a wide range of industries for various applications, such as automotive part assembly, electronics assembly (e.g., connectors and switches), and packaging (e.g., sealing of plastic containers).

H. *Solvent Welding*

In solvent welding, the welding process is carried out with the help of a solvent that can temporarily dissolve the polymer at room temperature. In the welding process, solvent is first applied to the surfaces to be joined and the polymers on these surfaces are dissolved.

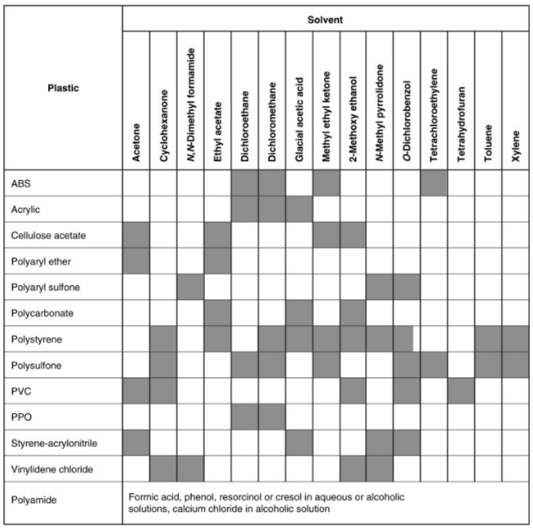
When the polymer is dissolved, the polymer chains can move freely in the liquid. When the part joining surfaces are brought into contact with each other, the dissolved chains mix with each other. When the solvent in the polymer is waited for a while to evaporate, the polymer chains will lose their mobility again [34]. Thus, a weld seam, a solid mass consisting of "entangled polymer chains", will be formed between the surfaces of the parts.

Solvent welding relies on the principle that certain organic solvents can dissolve and soften thermoplastic materials. When two polymer surfaces are brought into contact and a solvent is applied, it softens the polymer surfaces, allowing them to mix and fuse. As the solvent evaporates, the polymer surfaces solidify, forming a strong and permanent bond.

Solvent welding is primarily used for thermoplastic materials that are soluble in the chosen solvent. Common materials include PVC, CPVC (chlorinated polyvinyl chloride), ABS (acrylonitrile butadiene styrene), and some types of acrylics. It is essential to use a solvent that is compatible with the specific polymer being joined (Table 2).

Solvent welding requires very little equipment. Solvents or cements are usually applied by using brushes, wipes, or dispensers. Suitable personal protective equipment is required, as specified by the suppliers' instructions and safety data sheets. Adequate ventilation is also essential to ensure the extraction of solvent fumes from the work area.

Table 2. Solvents for welding of different plastics [35]



Plastic	Solvent														
	Acetone	Cyclohexanone	*N,N*-Dimethyl formamide	Ethyl acetate	Dichloroethane	Dichloromethane	Glacial acetic acid	Methyl ethyl ketone	2-Methoxy ethanol	*N*-Methyl pyrrolidone	*O*-Dichlorobenzol	Tetrachloroethylene	Tetrahydrofuran	Toluene	Xylene
ABS					■	■		■				■			
Acrylic					■	■	■								
Cellulose acetate	■			■				■	■						
Polyaryl ether	■			■											
Polyaryl sulfone			■							■	■				
Polycarbonate				■			■		■						
Polystyrene		■		■		■	■	■	■	■	■			■	■
Polysulfone		■			■	■		■			■	■		■	■
PVC	■	■							■		■		■		
PPO					■	■									
Styrene-acrylonitrile	■						■			■	■				
Vinylidene chloride		■	■						■	■					
Polyamide	Formic acid, phenol, resorcinol or cresol in aqueous or alcoholic solutions, calcium chloride in alcoholic solution														

i. Friction Stir Welding (FSW)

Friction stir welding, a solid-state welding technology used for metals, has started to be used in recent years for the welding of polymer matrix composites. Especially polymers such as Polyethylene (PE), Polycarbonate (PC) and Polymethyl Methacrylate (PMMA) and different polymers can be welded together.

Friction stir welding is performed by a rotating cylindrical tool with a pin (probe) with a diameter smaller than the shoulder diameter. During welding, the probe on the tool rotates and creates heat between the workpieces, thus softening the material and mixing the materials and ensuring their joining. The welding process is performed by moving the tool forward along the connection line at the preset welding speed, after a short waiting period after the probe enters the material (Figure 11).

Tool design, welding process parameters and reinforcement content are some of the important factors that affect the material flow and microstructure in welding of the polymer composite materials.

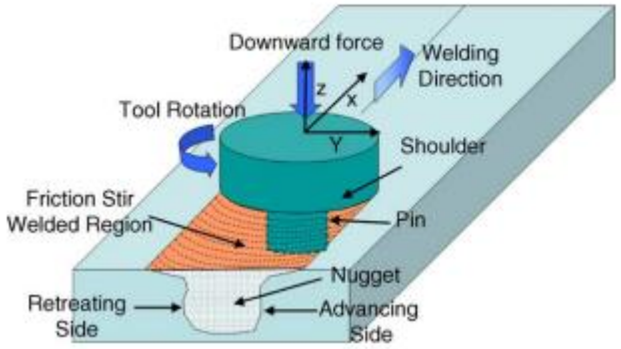


Figure 11. Schematic representation of friction stir welding [36]

III. CONCLUSION

Polymer matrix composites are preferred especially in the automotive, space and aircraft industries due to their higher strength properties compared to polymer materials. Therefore, combining these materials is becoming increasingly important today. both the lack of sealing and the stress concentrations created by the holes drilled into the composite parts under load limit the usage areas of Mechanical fastening. Joining with adhesive is very difficult to maintain the structural integrity of the structures and processing times can be quite long. For this reason, the welding process is preferred because it is easier to apply, faster and provides higher strength than other joining methods (mechanical fastening and adhesive joints). In this study, the welding methods used in joining polymer materials were examined in line with the emerging needs and the newly used welding techniques were tried to be introduced.

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