

JOINING OF PLASTICS AND COMPOSITES

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Keywords: polymers, plastics, composites, hot tool welding, hot gas welding, extrusion welding, induction welding, resistance welding, ultrasonic welding, vibration welding, spin welding, laser welding, dielectric welding, microwave welding.

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Summary

The use of polymeric materials is nowadays increasingly in a many important applications including packaging, building, appliance, electronics, automotive, aerospace and much more. Polymers already have a range of applications that far exceeds that of any other class of material available. Joining is a critical step in the manufacture of components from polymers and polymeric composites. As the requirements for the component increase, so do the requirements for joining, especially in structural applications. The methods for joining plastics and composites can be divided into three major categories: mechanical fastening, adhesive and solvent bonding, and welding. Welding is an effective method of permanently joining plastic components. There are various welding methods. By reviewing and comparing all

commercially available welding processes, this text helps the reader select the best-suited process for the application and provides an understanding on the limitations and benefits of each process. The focus on practical aspects such as weldability, and testing makes this text an indispensable tool for everyone involved in welding of plastics. At the same time, it also conveys the basic theoretical principles of plastics welding such as squeeze flow, molecular diffusion, and heat transfer mechanisms. Each section of this chapter was developed with information dealing with basic welding aspects including materials, process phenomenology, equipment, and joint design. While not all encompassing, the text provides the basic information along with references that can be used to gather additional information or details.

1. Introduction

The use of polymeric materials is nowadays increasingly in a many important applications including packaging, building, appliance, electronics, automotive, aerospace. Already around 1983 the world's yearly volumetric consumption of polymers exceeded the volumetric consumption of iron and steel. The worldwide polymers production in 2006 reached 300 million tons.

Polymeric materials have many advantages including: high specific strength (strength/density ratio), high specific modulus (modulus/density ratio), design flexibility, reduced manufacturing costs, excellent corrosion, solvent and environmental resistance, thermal and electrical insulation, durability etc.

Nowadays, there are thousands of grades of polymers available at the market. These cover a wide range of properties, from soft to hard, ductile to brittle, and weak to tough. The wide variety of polymers and polymeric composites makes it possible to select and even customize the material to the specific application. Therefore, these materials are being used in more and more applications under more and more stringent requirements. Continuing efforts in discovering new polymers as well as modifying existing polymers to create new material combinations further increases the potential uses of these materials.

In polymer engineering, the design of a one-piece item for molding is the ideal situation because it precludes an assembly operation. However, mechanical limitations and other considerations often make it necessary to join polymeric parts, either to each other or to other polymeric or metallic parts, to complete the assembly. In such instances, the joining process can be an efficient production technique if a few precautions are taken and established procedures are followed.

Joining is a critical step in the manufacture of components from polymers and polymeric composites. As the requirements for the component increase, so do the requirements for joining, especially in structural applications. Joints are necessary always when: part integration is impossible because of complexity and/or high costs, using different materials in the same component, disassembly is required, and repair of damage is needed.

Joining is generally the final step in any fabrication cycle. The effectiveness of the joining operation can have a large influence on the application of any polymer or composite material. There is a variety of joining techniques for polymer products. Figure 1 provides a classification of these methods.

The methods for joining plastics and composites can be divided into three major categories: **mechanical fastening**, **adhesive and solvent bonding**, and **welding** (Figure 1).

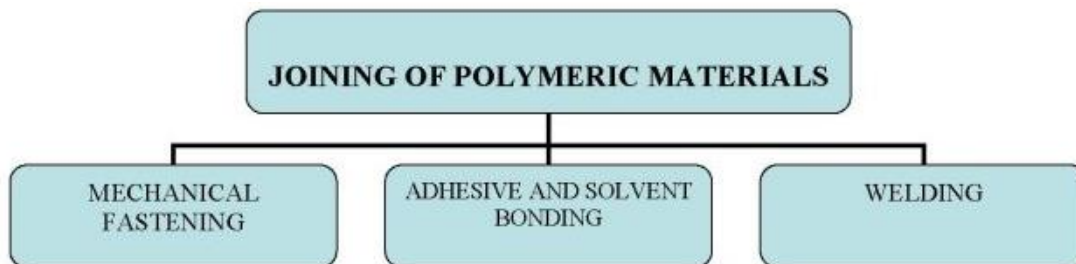


Figure 1. Classification of polymeric materials joining techniques

Mechanical fastening presumes the use of additional parts (fasteners) such as polymeric or metallic screws, bolts, washers, rivets or it relies on integrated design elements such as snap-fit or press-fit joints. Mechanical fastening can be used to join both similar and dissimilar materials. For example, mechanical fastening is commonly used when joining a plastic to a metal, producing either permanent joints or connections that can be opened and sealed again. The advantages of this approach are that no surface treatment is required and disassembly of the components for inspection and repair is straight forward. The main limitations are increased weight, the presence of large stress concentrations around the fastener holes, and subsequent in-service corrosion problems. The typical applications of mechanical fastening are in the aerospace, automotive, and construction industries.

In **adhesive bonding**, an adhesive is placed between the parts to be bonded (adherends) where it serves as the material that joins the parts and transmits the load through the joint. In **solvent bonding**, the application of a solvent at the bond line induces sufficient mobility for the polymer chains to interdiffuse. Because the solvent must strongly plasticize the polymer surface, this joining technique is primarily applied to glassy amorphous thermoplastics, such as polycarbonate (PC), acrylic (AK), and polystyrene (PS) resins. These techniques have found wide use by virtue of their low cost and adaptability to high-speed production. In addition, adhesive and solvent bonds provide a relatively uniform distribution of stresses over the assembled areas and a high strength-to-weight ratio. Solvent bonding is applicable only for joining of amorphous thermoplastics, whereas adhesive bonding can be used with almost all plastics.

In **welding**, sometimes called also a **fusion bonding**, heat is applied to melt the polymeric material at contacting surfaces enabling through intermolecular diffusion and polymeric chains entanglement processes to form a joint. The scope of this text is polymeric welding technology only.

2. Polymers

Polymers are a group of organic, semi-organic, or (rarely) inorganic **chemical substances** containing many large polymer molecules (**macromolecules**) often form into a chain-like structure. These molecules are formed together by linking together many small molecules, called monomer molecules, by process named polymerization. The name polymer comes from the combination of the Greek words “polys”, which means many, and “meros”, which means part. Polymers may be of **natural** or **synthetic** (man-made) origin. Polymers in the natural world have been around since the beginning of time. Such natural polymers (**biopolymers**) comprise such diverse groups as nucleic acids, cellulose, natural rubber, and lignin (component of wood). Some natural polymers are commercially used, either directly (e.g. cotton) or after a chemical modification (e.g. cellulose acetate, vulcanized natural rubber). Synthetic polymers have been studied since 1832. Today, the industry of **synthetic polymers** has grown to be larger than the aluminum, copper and steel industries combined.

Polymers are rarely used alone. They do not fulfill per se all technological requirements and become commercially useful only after they are admixed with certain supplementary materials, **additives** and **modifiers**, in various compounding and mixing processes, in which we produce **polymeric materials**.

Polymers already have a range of applications that far exceeds that of any other class of material available. Current applications extend from adhesives, coatings, foams, and packaging materials to textile and industrial fibers, elastomers, and structural plastics. Polymers are also used for most composites, electronic devices, biomedical devices, optical devices, and precursors for many newly developed high-tech ceramics.

Just as nature has used biological polymers as the material of choice, mankind will chose polymeric materials as the choice material. Humans have progressed from the Stone Age, through the Bronze, Iron, and Steel Ages into its current age, the Age of Polymers - an age in which synthetic polymers are and will be the material of choice.

Polymeric materials have a vast potential for exciting new applications in the foreseeable future. Polymer uses are being developed in such diverse areas as: conduction and storage of electricity, heat and light, molecular based information storage and processing, molecular composites, unique separation membranes, revolutionary new forms of food processing and packaging, health, housing, and transportation. Indeed, polymers will play an increasingly important role in all aspects of our life.

Polymeric materials can be separated into three different groups depending on their behavior when heated (Figure 2).

Thermoplastics are polymeric materials with linear macromolecules synthesized by addition or condensation polymerization. This process forms strong covalent bonds within the chains and weaker secondary bonds between the chains. Usually, these secondary forces can be easily overcome by thermal energy, making thermoplastics

moldable at high temperatures. Thermoplastics soften upon heating and can be remolded and recycled. Thermoplastics solidify as they cool, restricting the motion of the long molecules. When heated, these materials regain the ability to “flow”, as the molecules can slide past each other easily. Thermoplastics will also retain their newly reformed shape after cooling. The transformation solid – melt is **reversible**. They can be **amorphous** (Table 1) or **semi-crystalline** (Table 2).

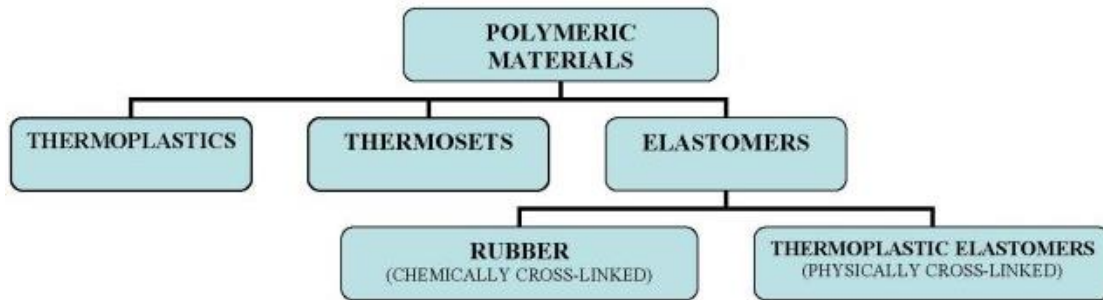


Figure 2. Common classification of polymeric materials

Abbreviation	Amorphous Thermoplastics	Glass Transition T_g , °C	Group (by application)
PVC	Poly(vinyl-chloride)	81	Commodity Thermoplastics
PS	Polystyrene	100	
CA	Cellulose acetate	105	Transient Thermoplastics (* main phase T_g)
S/B	Styrene/Butadiene copolymer	90*	
ABS	Acrylonitrile/Butadiene/Styrene copolymer	85*	
SAN	Styrene/Acrylonitrile copolymer	106	
ASA	Acrylonitrile/Styrene/Acrylate copolymer	100*	
PMMA	Poly(methyl-methacrylate)	105	
PA 6-3-T	Amorphous polyamide	147	Engineering Thermoplastics
PC	Polycarbonate	150	
PPE(PPO)	Poly(phenylene-ether)	175	
PSU	Polysulfone	190	
PES	Poly(ether-sulfone)	230	
PEI	Poly(ether-imide)	217	
PAI	Poly(amide -imide)	277	

Table 1. Amorphous thermoplastics

Abbreviation	Semi-crystalline Thermoplastics	Glass Transition T_g , °C	Group (by application)
PE-LD	Low-Density Polyethylene	- 100	Commodity
PE-HD	High-Density Polyethylene	- 115	Thermoplastics

PP	Polypropylene	- 18	
PTFE	Poly(tetrafluorethylene)	- 97	Transient Thermoplastics
PET	Poly(ethylene-terephthalate)	69	
PA 11	Polyamide 11	43	Engineering Thermoplastics
PA 12	Polyamide 12	41	
PA 6	Polyamide 6	47	
PA 66	Polyamide 6.6	57	
PA 610	Polyamide 6.10	50	
PA 46	Polyamide 4.6	85	
POM	Poly(oxymethylene)	- 38	
PBT	Poly(butylene-terephthalate)	22	
PPS	Poly(phenylene-sulfide)	88	
PEEK	Poly(ether-ether-ketone)	143	

Table 2. Semi-crystalline thermoplastics

Amorphous thermoplastics have molecules that remain disorderly as they cool, leading to a material with random molecular structure. An amorphous thermoplastic material solidifies, or vitrifies, as it cools below its glass transition temperature, T_g (Figure 3).

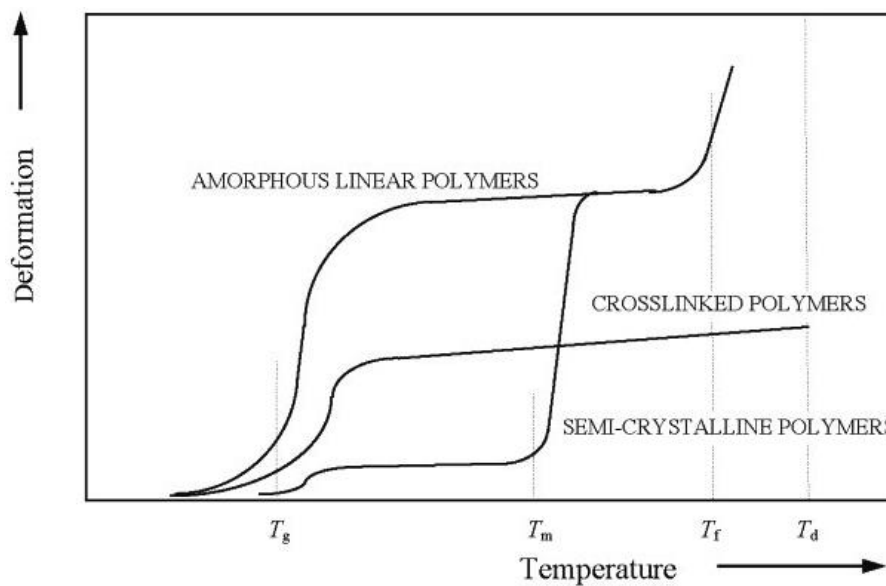


Figure 3. Deformational characteristics of polymers

Semi-crystalline thermoplastics, on the other hand, solidify with certain order in their molecular structure. Hence, as they cool, they harden when the molecules arrange in a regular order below what is usually called the melting temperature, T_m . However, the molecules in semi-crystalline thermoplastics not ordered remain in amorphous regions. These regions within the semi-crystalline domains solidify at the glass transition temperature (T_g). Most semi-crystalline thermoplastics have a glass transition

temperature below the freezing point, and, behave at room temperature similarly to rubbery or leathery materials.

A few common applications of thermoplastics include: parts for common household appliances, bottles, cable insulators, tape, blender and mixer bowls, medical syringes, mugs, textiles, packaging, and insulation.

Thermosets, besides the secondary bonds as thermoplasts, have also a stronger, chemical linkage between the chains. Strong covalent bonds chemically hold different chains together in a thermoset material. The chains may be directly bonded to each other or be bonded through other molecules. This "cross-linking" between the chains allows the material to resist softening upon heating. The transformation solid – melt is **irreversible**. Because they do not soften under heat and pressure and cannot be remolded or recycled. Thus, thermosets must be machined into a new shape if they are to be reused or they can serve as powdered fillers. The high density of crosslinking between the molecules makes thermosetting polymers stiff and brittle. Thermosets also exhibit glass transition temperatures which sometimes exceed thermal degradation temperatures. They comprise alkyd resins, phenolic resins (PF), amino resins (MF, UF), epoxies (EP), unsaturated polyesters (UP), polyurethanes (PUR), and allylics, e.g. diallyl phthalate (DAP).

Although thermosets are difficult to reform, they have many distinct advantages in engineering design applications including: high thermal stability and insulating properties, high rigidity and dimensional stability, resistance to creep and deformation under load, and light-weight. A few common applications for thermosets include epoxies (adhesives), automobile body parts, adhesives for plywood and particle board, and as a matrix for composites in boat hulls and tanks.

Elastomers are slightly cross-linked polymers, which permits almost full molecular extension. However, the links across the molecules hinder them from sliding past each other, making even large deformations reversible. One common characteristic of elastomeric materials is that the glass transition temperature is much lower than room temperature. The irreversible **chemical cross-linking** of elastomer macromolecules to polymers with wide mesh sizes results in **rubber**. **Thermoplastic elastomers (TPE)** are elastomeric materials from polymers with reversible **physically cross-links** (Table 3).

Abbreviation	Thermoplastic Elastomers Group
TPE-E	Ester thermoplastic elastomers
TPE-S	Styrene thermoplastic elastomers
TPE-A	Polyamide thermoplastic elastomers
TPE-U	Urethane thermoplastic elastomers
TPE-O	Olefinic thermoplastic elastomers
TPE-V	Ethylene/Propylene/Diene thermoplastic elastomers

Table 3. Thermoplastic elastomers

Plastics are common name for **thermoplastics** and **thermosets**. The name “plastics” refers to their easy processability and shaping (Greek: “plastein” means to form, to shape). Therefore, plastic and polymer are not synonyms. Polymers are raw materials for plastics (thermoplastics and thermosets), but also for elastomers and many other products (thickeners, varnishes, binders etc.).

Polymer composites are a combination of two or more materials (reinforcing elements, fillers and composite matrix binders), in which distinct, structurally complementary substances, especially metals, ceramics, glasses, and polymers, combine to produce structural or functional properties not present in any individual component. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in coherence. Normally, the components can be physically identified and exhibit an interface between one another.

The composites are divided in four main categories:

- composites with particles,
- composites reinforced with fibers,
- layer composites, and
- sandwich composites.

There are two categories of constituent materials: matrix and reinforcement.

The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mold cavity or onto the mold surface. : Most commercially produced composites use a polymer matrix material often called the resin solution. There are many different polymers available depending upon the starting raw ingredients, but most common is polymer matrix with glass, carbon and aramide fibers. Most frequently used polymers for composite matrix are: polyester: polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, PEEK and others.

The reinforcement materials are often fibers but also they can be common ground minerals. Fiber reinforced composite materials can be divided into two main categories normally referred to as short fiber reinforced materials and continuous fiber reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fiber styles are typically available in a variety of forms, being pre-impregnated with the given matrix (resin), dry, uni-directional tapes of various widths, plain weave, and harness satins, braided, and stitched. The short and long fibers are typically used in compression molding and sheet molding operations.

Composite materials can be welded. Most common methods are highlighted below:

- ultrasonic,
- vibration,
- rotation, and
- electrical resistance welding.

Ultrasonic welding is widely used for precision assembly of relatively small plastic components. Vibration welding is a process well suited for applications such as automotive assembly. Lower frequency vibrations with displacements of millimeters rather than microns are used to generate interface friction. In rotation welding, sometimes known as spin or friction welding, heat is generated by the rapid rotation of one component against the other under an applied pressure. In electrical resistance welding it is attractive to use carbon fibers as a heating element.

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Biographical Sketches

Mladen Sercer was born in Zagreb, Croatia on September 29th, 1953. He graduated from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia in 1977. He obtained a Master of Science (M.Sc.) degree in 1984 from the Faculty of Technology, University of Zagreb and a PhD degree in 1989 from the Faculty of Mechanical Engineering and Naval Architecture, in the field of mechanical engineering (polymer technology) from the University of Zagreb.

He worked at the Faculty of Mechanical Engineering and Naval Architecture since 1978, first as an assistant, from 1985 as scientific research assistant, from 1989 as assistant professor, from 1996 as associate professor, and since 2001 as full professor in the field of mechanical engineering, section of *Mechanical Technologies and Processing Systems* at the Department of Technology. In June 2006 he was promoted in permanent position of full professor. Since 2001 he is the head of the Chair for Polymer Processing and since 2006 also the head of the Department of Technology. From 1984-1985 he researched at Institute for Polymer Processing (Institut für Kunststoffverarbeitung - IKV), Aachen, Germany, sponsored by German Academic Exchange Foundation (Deutscher Akademischer Austauschdienst - DAAD). He published as author and co-author several books and monographs and number of articles in scientific journals and at international symposia. He has also delivered a number of lectures in country and abroad. In his professional, teaching and scientific work he focuses mainly on polymer processing technology, development and designing of polymeric parts and molds, rapid

prototyping and recycling of polymers.

Prof. Šercer is associate member of the Academy of Technical Sciences of Croatia. He is a member, founder and secretary of the Society of Polymer Engineers, Zagreb (Croatia). He is a member of the Society of Plastics and Rubber, Zagreb (Croatia), the Croatian DAAD club and Polymer Processing Society, Akron, USA. He was the editor of the column *From the World of Plastics and Rubber*, editor for *Categorized Articles*, and editor-in-chief of the journal *Polimeri (Polymers)*, Zagreb (Croatia).

Pero Raos was born in Split, Croatia on May 3rd, 1961. He graduated from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia in 1984. He obtained a Master of Science (M.Sc.) degree in 1987, and a PhD degree in 1991 in the field of mechanical engineering (polymer technology) from the same University.

In November 1993 he became the assistant professor of the Mechanical Engineering Faculty of Slavonski Brod at University of Osijek, Croatia. In January 1998 he was entitled as associate professor and in November 2001 as full professor at the same Faculty. In February 2006 he was promoted in permanent position of full professor. Since June 2005 he is the head of the Department of Technology. From 1989-1990 and 1993-1994 he researched at Institute for Polymer Processing (Institut für Kunststoffverarbeitung - IKV), Aachen, Germany, sponsored by German Academic Exchange Foundation (Deutscher Akademischer Austauschdienst - DAAD) and Alexander von Humboldt Foundation. In 1993 he researched shortly at Institut de Génie Civil, Liege, Belgium. He is the author and co author of several books and a number of scientific and professional papers. He has also delivered a number of lectures in country and abroad. In his professional, teaching and scientific work he focuses mainly on polymer processing technology, development and designing of polymeric parts and molds, numerical methods and application of finite element methods in designing and application of adhesive bonding technology.

Prof. Raos is a member of the Scientific Council for Technical Sciences of the National Science Council of the Republic of Croatia. He was the Secretary General of Plastic and Rubber Engineers Society of Croatia (1992-1993). Prof. Raos is the president of Telemedicine Association of Zagreb (Croatia) and a member of Polymer Processing Society, Akron (USA), and European Scientific Association for Material Forming (France), Croatian Humboldt Club, Zagreb (Croatia), Society of Polymer Engineers, Zagreb (Croatia), Croatian Maintenance Society, Zagreb (Croatia) and Croatian System Society, Zagreb (Croatia). He is editor-in-chief of the journal *Technical Gazette* (Croatia).