JOINING OF PLASTICS AND COMPOSITES

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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).

![Classification of polymeric materials joining techniques](image)

**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 straightforward. 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.

![Figure 2. Common classification of polymeric materials](image-url)

Polymeric materials have a vast potential for exciting new applications in the foreseeable future. Polymer uses are being developed in such diverse areas as:
condensation 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).

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

Table 1. Amorphous thermoplastics
Abbreviation | Semi-crystalline Thermoplastics | Glass Transition $T_g$, °C | Group (by application)
--- | --- | --- | ---
PE-LD | Low-Density Polyethylene | -100 | Commodity Thermoplastics
PE-HD | High-Density Polyethylene | -115 |
PP | Polypropylene | -18 |
PTFE | Poly(tetrafluorethylene) | -97 | Transient Thermoplastics
PET | Poly(ethylene-terephthalate) | 69 |
PA 11 | Polyamide 11 | 43 |
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

Figure 3. Deformational characteristics of polymers
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).

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).
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, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, PEEK and others.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Thermoplastic Elastomers Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPE-E</td>
<td>Ester Thermoplastic Elastomers</td>
</tr>
<tr>
<td>TPE-S</td>
<td>Styrene Thermoplastic Elastomers</td>
</tr>
<tr>
<td>TPE-A</td>
<td>Polyamide Thermoplastic Elastomers</td>
</tr>
<tr>
<td>TPE-U</td>
<td>Urethane Thermoplastic Elastomers</td>
</tr>
<tr>
<td>TPE-O</td>
<td>Olefinic Thermoplastic Elastomers</td>
</tr>
<tr>
<td>TPE-V</td>
<td>Ethylene/Propylene/Diene Thermoplastic Elastomers</td>
</tr>
</tbody>
</table>

Table 3. Thermoplastic Elastomers
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.

3. Polymeric Materials Welding

3.1. Basic Principles

Welding of plastics and their composites is the process of joining parts through heating in order to melt (or eventually soften) and fuse the polymer at the interface. Even this description is rather simplified; it captures the essence of thermoplastics welding processes.

The weldability of polymeric materials depends on whether they are thermosets, thermoplastics or elastomers. In the case of thermoset resins, a chemical reaction occurs during processing and curing, that is, as a result of irreversible cross-linking reactions in the mold. Neither molded thermoset or chemically cross-linked elastomer (rubber) components can be reshaped by means of heating, because degradation occurs. It follows that thermoset and vulcanized rubber components can only be joined using adhesive bonding or mechanical fastening methods.

Thermoplastics and physically cross-linked elastomers (thermoplastic elastomers), on the other hand, can be softened and melted as a result of the weakening of secondary van der Waals or hydrogen bonding forces among adjacent polymer chains (Figure 3). Therefore, thermoplastics and thermoplastic elastomers can be remolded by the application of heat, and they can be fusion welded successfully.
Polymers are low-energy substrates, with surface free energies usually less than 50 mJ/m². The creation of a successful joint depends on four factors: the chemical nature of the polymer, the surface free energy, the surface topography, and contamination of the polymer surface by dust, oil, and grease. These factors markedly affect the effectiveness of the adhesive and solvent bonding methods. Fusion welding, however, is much more tolerant of factors such as surface contamination and material variations from sample to sample.

Polymeric materials that possess similar solubility parameters can be joined using solvent or fusion welding. Interdiffusion of polymer chains plays a major role in achieving intrinsic adhesion and in promoting chain diffusion, either by applying a suitable solvent or by heating the polymer sample.

As mentioned previously, only thermoplastics and thermoplastic elastomers (TPE) can be joined using the fusion welding process. The glass transition temperature ($T_g$), in amorphous polymers and the melting temperature ($T_m$), in crystalline polymers must be exceeded so that the polymer chains can acquire sufficient mobility to interdiffuse (Figure 3). A variety of methods exist for welding thermoplastics, thermoplastic composites, and thermoplastic elastomers. Thermal energy can be delivered externally via conduction, convection, and/or radiation methods, or internally via molecular friction caused by mechanical motion at the joint interface. In the case of external heating, the heat source is removed prior to the application of pressure, and longer welding times are balanced by the greater tolerance to variations in material characteristics. Internal heating methods depend markedly on the material properties. Heating and pressure are applied simultaneously, and shorter welding times are generally involved during the joining process.

3.2. Fundamental Welding Steps

The most of welding processes have in common five distinct steps. For some of welding techniques these process steps are sequential, while for other techniques some of the steps may occur simultaneously. The basic welding steps are:

- Surface preparation
- Heating
- Pressing
- Intermolecular diffusion
- Cooling

Surface preparation is the first step in getting plastic parts ready for welding. This step is especially important when using manual or semi-automated processes because the level of manual handling required in these processes increase the possibility of contamination. Surface preparation mostly includes machining and/or cleaning (degreasing). Surface machining insures that it is square, or that it fits in the weld surface from the other part, or in some cases it may be required to apply a groove or chamfer like in the process of hot gas welding. Typically, cleaning is carried out by
applying a solvent to degrease the surface. In automated welding processes, surface preparation is rarely used.

There are several ways to heat plastics for welding. In all welding methods, only the surface near the weld interface has to be heated in order to melt or soften polymeric material because: the heating and melting of a thin layer is more efficient than heating of a large mass of material. Due to relatively small thermal conductivity of polymers it is faster and more efficient to melt the plastic near the joint than to wait for convection or conduction to melt the polymer everywhere. Melting the plastics everywhere would make it impossible to support the part during heating stage to avoid parts deformation. Welding processes are often classified by the heating method that is used too (Section 3.3).

Heating is usually considered the most critical step in the welding process because welding is not possible without the formation of a thin melted layer on each joining parts. This layer is necessary to make intermolecular diffusion and chain entanglements possible.

Once the heated zones are established, pressure must be applied to form close contact between the joining parts, while for composite parts it can also suppress deconsolidation. This is done in two phases. In the first phase roughness on the surface are deformed and very close contact of the joining parts is achieved. During the second phase parts of the melt layer are squeezed out and any possible entrapped gases and contaminated plastic from the joint area are displaced.

After plastic-to-plastic contact is achieved at the joint interface, intermolecular diffusion and macromolecular chains entanglement is necessary to complete the process and to form a good and durable weld. Autohesion is the phenomenon describing the intermolecular diffusion and chains entanglement across a thermoplastics interface forming a strong bond. Unlike adhesion, which relies on surface energetics, autohesion relies on chains entanglement and secondary bonds for polymer chains of similar materials. Under ideal conditions, the diffusion is complete when the interface is no longer discernible from the bulk material.

The final stage in the welding process is the cooling and re-solidification of the polymer at the joint. During this final step, semi-crystalline matrices re-crystallize to obtain their final micro-structure. Amorphous plastics retain any molecular orientation that was previously induced. In addition, thermally induced residual stresses and distortion remain “frozen” in the parts.

3.3. Classification of Welding Techniques

Welding techniques are often classified and identified by the heating method that is used. All the welding methods can be divided into two general categories: external and internal heating. External heating methods rely on convection and/or conduction to heat to the weld surface. These welding techniques include: hot tool (hot plate) welding, hot gas welding, extrusion welding, induction welding, and resistance welding.
Internal heating methods are further divided into two categories: internal mechanical heating and internal electromagnetic heating. **Internal mechanical heating methods** rely on the conversion of mechanical energy into heat through surface friction and intermolecular friction. These welding techniques include: ultrasonic welding, vibration welding, and spin welding. **Internal electromagnetic heating methods** rely on the absorption and conversion of electromagnetic radiation into heat. These welding techniques include: infrared/laser welding, dielectric (radio frequency) welding, and microwave welding (Figure 4).

![Figure 4. Classification of different welding methods of polymeric materials](image)

**Bibliography**


**Biographical Sketches**

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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).