

1 Multicomponent Technologies

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1.1 Introduction

In special injection molding processes (more precisely, in the case of multicomponent technologies), new processing alternatives continue to arise that enable material combination, and the economical manufacture of components with varying functionalities. Owing to its increasing significance in numerous areas and due to various motivations, multicomponent technology is often referred to as key technology. In the research literature, differing outlines, or classifications of the special processes and the according tool and handling technologies, can be found. Differentiations made in accordance with the process sequence are just as common as those made in accordance with the employed material classes or the required machine and handling technologies.

All these classifications have one thing in common—namely, their inability to provide fundamental insight into the processes that take place during the formation of the composite. This is a consequence of their specific methods of approach. Despite differing machine technologies and processing sequences that diverge from one another, the procedures during formation of the component are, for the most part, based upon identical basic mechanisms. Consequently, the formation of the composite can be influenced in a similar way. Therefore, each specific technical method must be analyzed only with regard to these processes, in order to provide information concerning the correlating processes that take place in the component and the possible effects that influence these processes.

We aim to provide the reader access to differential, in-depth information. Accordingly, this chapter has been structured into three sections. The first section “Basic Bonding Mechanism” is dedicated to theoretical information and describes the basic mechanisms.

Subsequently, in the second section “Influences of Material and Process Control on the Basic Bonding Mechanism”, the focus shifts to interpretation and derives the effects of various material and processing parameters. Finally, the third section “Machines and Processes” closes with a pragmatic description of specific technical methods.

The chapter not only provides a fundamental knowledge base, but also enables the reader to understand methods that will become available in the future.

1.2 Motivation

Injection molded plastic-plastic composites are manufactured for very different purposes. The combination of properties and the integration of functions are the main motives. Components with different properties—color, hardness, flowability, thermal and electric properties, viscosity, etc.—are combined. Combining properties in this manner makes it possible to integrate functions specifically in the component or incorporate functional elements. For instance, in hard-soft composites, the hard component provides the strength while the soft component acts as a sealant or insulation, or performs haptic functions. With regard to optical or visual functions, various colors, transparent areas, or light-conducting components are combined with one another. Electric and magnetic components are employed for antistatic or shielding functions. In addition to functional surface modifications, decorative functions are utilized in back injection and back imprinting.

In most cases, the driving force behind combining plastics in an injection molding process is the aim to save costs by reducing the number of processing, handling, and assembly steps or joining processes.

In most applications, good adhesion between the components is desired. However, the opposite can also be the goal, in order to join movable elements by connecting them with nonadhesive or incompatible materials in one processing step, and, thus, reducing the number of assembly steps.

Many of these applications are consumer products (e.g., toothbrushes, toys, electronic devices, and kitchen utensils). Other examples can be found in medicine and automobile construction [1–5].

In general, the different processes or methods vary in the following ways:

- the material combinations used – compatible or incompatible materials;
- the actual combining of the plastics, which can take place in the plasticization cylinder, in the barrel in front of the screw, or in the mold;
- the chronological order of the joining of components – simultaneous or sequential; and
- the mold and handling technologies used.

Furthermore, depending on the process and method used, the components can either be in the same or different aggregate states at the time of joining.

1.3 Basic Bonding Mechanism

The adhesion between two components is generally defined by the adhesive strength (σ_H), which describes the resistance against separating loads, more precisely the inner strength (F_i) required to overcome the adhesion with regard to the real contact surface (A_W) [6]:

$$\sigma_H = F_i/A_W. \quad (1.1)$$

However, because these two factors can only be determined insufficiently or only with great effort in practice, composite strength (σ_V) is used as an evaluation parameter. It is defined by the outer strength (F_a) with regard to the initial cross section (A_N) [6,7]:

$$\sigma_V = F_a/A_N. \quad (1.2)$$

Thus, the composite strength defines the mechanical strength and conditionally or indirectly correlates with the actual adhesive strength, which is based upon adhesion phenomena [6].

The formation of the composite and the according composite adhesion of two components are both determined by the overlapping of various mechanisms and influencing factors, which in turn are essentially caused by the material properties, the processing method, and constructive factors. In most cases, these mechanisms and their reciprocal effects have not yet been fully understood [2]. Too little is known about bonding

mechanisms that occur in real life, and, above all, which proportion of the adhesion they contribute to [1]. The technological and constructive influences on the process are the locally differing flow and temperature conditions, which define the orientation conditions in the boundary layer of the composite partners. In contrast, the material properties determine the wetting behavior, the surface tension, and the adhesion properties. In plastic-plastic composites, an overlapping of material and process-dependent mechanism in correlation with constructive boundary conditions can be assumed [6].

When injection molding thermoplastic plastic-plastic composites, chemical primary valence bonds are unlikely [6,8]. The secondary valence forces that take effect in the various adhesion theories (i.e., van der Waals forces, dispersion and dipolar forces, and hydrogen bonds) can create effects in only a very limited range of tenths of a nanometer [6, p. 23]. For this reason, wettability and sufficient convergence between the composite partners are prerequisites for good composite formation. Principally, the formation of the interfacial layer between the joining partners can be compared to the formation of a joint line [9]. As is also the case when welding plastics, diffusion processes play a role. Sufficient molecular mobility and diffusion processes across the interfacial layer are necessary for these actions to take place [9]. Nevertheless, it remains unclear whether the diffusion speed is high enough to play an essential role in technical processes that are completed at a high processing speed.

The bonding mechanism in general takes place as a result of adhesion and cohesion phenomena. Adhesion in the context of plastic-plastic composites describes the bonding forces between two materials and is described in the following section. Cohesion describes the forces of attraction within a material, meaning the bond between atoms and molecules created by mutual attraction [1]. The effect of cohesive bonding mechanisms on plastic-plastic composites is not yet clear. According to Ref. [8], cohesive forces are not regarded as significant in correlation with the formation of the composite.

1.3.1 Adhesion

Adhesion is defined as the connection between two materials in contact with one another. Various adhesion theories exist that can contribute to composite formation and the required mechanisms. However, no single theory explains all ongoing processes. Adhesion, therefore, can

be considered the sum of various simultaneously occurring bonding forces, which are all based on different adhesion theories.

Adhesion is usually classed as one of two varieties: mechanical and specific adhesion [4,8]. Yet, other categorizations are common (i.e., chemical, physical, and mechanical adhesion) in the literature [e.g., 10]. Mechanical adhesion describes the intrusion of a component into the pores and depressions of the other component, respectively. Thus, this form of adhesion is essentially based upon the surface roughness and surface structures of the components. Specific adhesion is divided into chemical, physical, and thermodynamic reciprocal effects. Moreover, it is classified into the following theoretical approaches:

- Chemisorption—This theory is based on the formation of chemical bonds in the interface, but, according to Ref. [8], has not yet been verified for plastic-plastic composites.
- Polarization—This theory (by De Bruyne) states that owing to polarity, molecular physical interactions between the materials result in adhesion processes. Here, sufficient wetting is also a requirement. This is the case if the polarities of both components are identical [4,11]. When combining polar and nonpolar plastics, adhesion as described in the polarization theory is not possible [6]. Functional groups situated on the surface (carboxyl, hydroxyl, and carbonyl groups) can contribute to improved composite adhesion [8]. The theory supplies an essential contribution to adhesion for plastic-plastic-composites.
- Electrostatic—This theory (by Derjaguin) focuses on the formation of an electric double layer in the interface that has been induced by the potential differences between the components [8]. The hypothesis states that the more similar the materials are, the smaller the double layer will be, and thus the adhesive strength as well [8]. This theory has been criticized because it cannot explain the adhesion between similar components [6]. The electrostatic theory is not being followed up in current research with regard to plastic-plastic composites [8].
- Thermodynamic—This theory is based upon the equation by Dupré, which defines the work of adhesion for separating two surfaces in correlation of interface and surface stresses. Good adhesive strength requires an interface stress

that is close to zero, which occurs when the polar and dispersed proportions of the according surface stresses are equal [6]. Owing to the very limited range of intermolecular forces (van der Waals forces, hydrogen bonds, and primary valence forces), sufficient closeness of the molecular chains or sufficient contact between the components is a fundamental requirement [4,11]. With regard to plastic-plastic composites no clear statement is given in the literature.

- Weak boundary layer theory—This theory assumes the formation of an intermediate layer in the interface that counteracts direct contact between the joining partners or composite materials. Reasons for this occurrence can be impurities in the surface, air or gas pockets due to poor wetting, or products of reactions or substrates in the surrounding air. This theory is often used when adhesion phenomena cannot be explained by other theories [8].
- Diffusion—In literature, the diffusion theory is often referred to as part of specific adhesion, and is based upon different models. Due to its high significance concerning composite formation in plastic-plastic composites, it will be described in depth in [Section 1.3.2](#).

1.3.2 Diffusion

The term diffusion generally refers to the autonomous equalization of the concentration in the form of directed molecular movement. The driving force is the difference in concentration between different phases.

With regard to plastic-plastic composites, the diffusion theory implies a diffusion of the molecules beyond the interface of the contacting elements. On a molecular level, mutual diffusion of molecular chains close to the surface or mutual penetration into the surface layer of the other component takes place.

After diffusion has completed, there is no clear interface between the composite partners. A boundary layer with molecule segments of both components is available. The interface consists of a mixture of molecules or molecular segments of both components. Moreover, the molecule chains are intertwined with one another. The entanglement of the molecules results in good composite strength [7]. Diffusion is a thermodynamic process, not a phenomenon that only takes place on the surface

[12]. The prerequisite for diffusion is contact between molecules [1]. Diffusion processes are possible if a thermodynamic compatibility of the components and a sufficient amount of molecular mobility are available. A temperature (T) higher than crystallite melting temperature (T_C) – $T > T_C$ applies for semicrystalline plastics, and a temperature (T) much higher than glass transition temperature (T_G) – $T \gg T_G$ is applicable for amorphous plastics. According to Ref. [6], diffusion processes were also observed in incompatible systems, but only for small ranges [53, p.381]. This can be explained by the partial diffusion of macromolecular segments [6].

Diffusion theory largely contributes to explaining composite strength. Sufficient molecular mobility is a prerequisite because diffusion speed depends on the mobility of the molecule or molecular segment [1], which is essentially determined by the interface temperature and the molecular weight [6]. The mathematical description of diffusion processes is Fick's law of diffusion; however, it is not directly applicable to diffusion processes in polymer chains [4,10]. The diffusion theory basically makes it possible to describe autoadhesion between two plastics. Yet, the theory displays deviations if semicrystalline plastics, strong chemical reciprocal effects, or both are present [13]. It is assumed that Fick's law of diffusion is applicable only if the thickness of the boundary or contact layer reaches the thickness of a bundle of molecules. Prior to diffusion, the chain form has a special significance. Entangled chains inhibit diffusion, and require more energy to accomplish the diffusion process, because they are intertwined with other chains and are restricted in terms of their mobility. In the moments before the surface layer width is achieved—as mentioned previously—the diffusion can be described using the reptation model [4,10]. The penetration depth is described using Einstein's Law (as described in the next section).

The transition in the area of the interface, which is caused by diffusion processes and is not clearly defined, leads to a reduction of the property differences of the components in this section. This is generally advantageous for the composite strength. Longer contact times, higher temperatures, a higher degree of chain flexibility, the level of branching, a low molecular weight [2], and a small discrepancy between the solubility parameters [12] all prove to be beneficial in diffusion processes. Factors that limit the mobility of the molecular chains (i.e., high levels of branching, high degrees of crystallinity, strong polar groups, and a high content of filling material) negatively affect diffusion [12].

In general, diffusion is temperature-dependent and correlates with the viscosity, meaning that it depends upon the type of process and process control. With regard to conventional joining processes such as welding, the diffusion periods are often too long, compared with processing time, to be able to explain the achievable composite strengths [7,10]. By injection molding plastic-plastic composites, the actual time in which high temperatures are used to achieve sufficient chain mobility is also normally quite small because of the typically low wall thickness and high cooling rates. Thus, the timeframe for diffusion processes can be expected to be very low.

1.3.2.1 Diffusion Theory—The Einstein Equation

The diffusion theory describes transposition processes, which occur when two polymers come into contact. The formation of the composite is influenced by: the number of molecular chains that have penetrated each other, the penetration time, and the types and sizes of the forces between the molecules. The hypothesis in this model employs a simplified perspective, stating that mainly entirely stretched, free chain ends take part in the diffusion process. This assumption enables an estimation of the diffusion coefficient. Einstein's Law describes the intermediate penetration depth \tilde{x} of the diffused chains in the diffusion partners in correlation with the diffusion coefficient (D) and time (t). The penetration depth increases with the square root of the contact time [1,10]:

$$\Delta\tilde{x} = \sqrt{(2*D*t)} \quad (1.3)$$

The penetration depth and diffusion layer thickness depend upon the compatibility of the polymers. In the case of compatible systems, this layer can equal several micrometers [1]; in partially compatible systems, several ångström, or up to several nanometer [12].

After a certain period of time, the number of diffused molecules will no longer change [4]. The deeper the depth of penetration and the higher the number of diffused chain segments, the better composite formation will be.

The number of diffused molecules can be determined at a specific point in time to estimate the adhesive strength. For this purpose, an intermediate penetration depth of an entirely stretched molecule and

knowledge of the intermediate deformation speed are needed. The precise basis for calculations can be found in literature [e.g., 10].

1.3.2.2 *The Reptation Model*

Fick's law of diffusion describes the flow of the material along a concentration gradient in diffusion processes in the dependency of the diffusion coefficient—this describes the tendency to diffuse and the diffusion speed. However, it cannot be directly applied to the diffusion of polymer chains, especially not for entangled polymer chains.

It is assumed that Fick's law of diffusion is initiated when the surface-layer width reaches the thickness of a molecule bundle. In the time preceding this moment, the chain form is of high significance. Molecular chains are larger and heavier than single molecules; thus, their tendency to diffuse decreases the longer they are and the higher their degree of entanglement is. Furthermore, they require more energy for diffusion processes. In regard to a good composite formation, entanglements with the molecular chains of the bonding partner are particularly advantageous.

The reptation model (according to De Gennes and Doi and Edwards) observes molecular movements in the melt at various points in time. Temperature-dependent reptation time refers to the time after the molecular chain has left its original orientation. In most cases, free molecular chains take a starkly tangled form. Their movement is described as snakelike or wormlike. Owing to the tangled structure of neighboring molecules, the chains are trapped in a form of a network. This is often illustrated with a pipe or hose that is surrounded by molecular chains, and it aims to represent the molecular chains' limited freedom of movement (Figure 1.1).

Two main movements are possible in the “pipe.” The chain ends can move freely, thus changing the form of the chain and eventually leaving the original “pipe” position. After an initial, heat-induced stretching process (Brownian molecular movement), the chain slowly but surely leaves its original orientation and, by the end of the reptation, has completely left its primary form. The reptation time can be calculated using the Arrhenius approach. By means of the reptation time and an intermediate penetration depth, estimations concerning the composite strength can be made. For further information, please refer to the relevant literature [4,10].

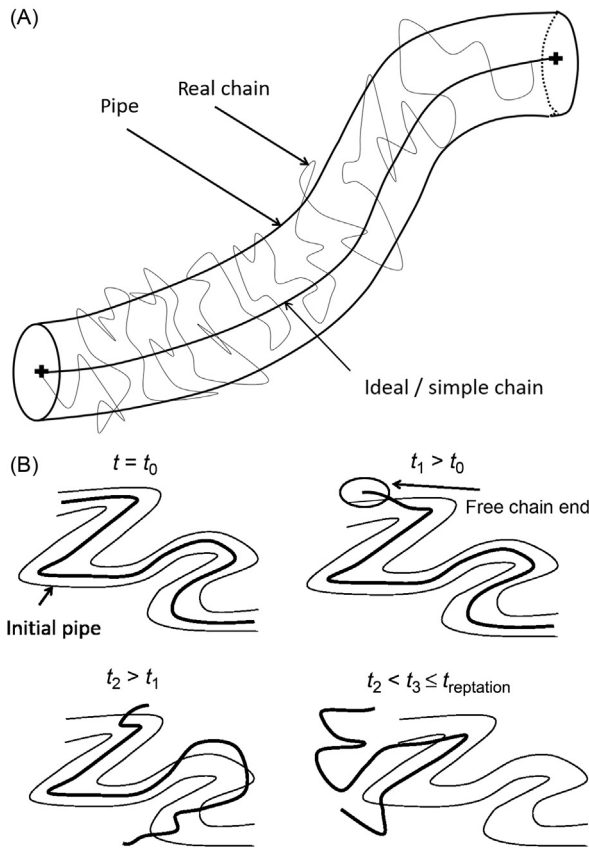


Figure 1.1 Reptation model according to Ref. [10]; compare with Ref. [14].

1.4 Influences of Material and Process Control on the Basic Bonding Mechanism

When injection molding plastic-plastic composites, adhesion is a function of the material, process control, and part design. These factors influence each other and define the local rheological and thermodynamic conditions [7]. As previously mentioned in the introduction to this chapter, all processing parameters, material effects, and basic conditions either directly or indirectly affect the interface, and thus the quality of the composite as well. In the following section, the influencing factors of the bonding determinants relevant in practice will be allocated to three bonding determinants: interface compatibility, interface temperature, and interface stress (Figure 1.2).

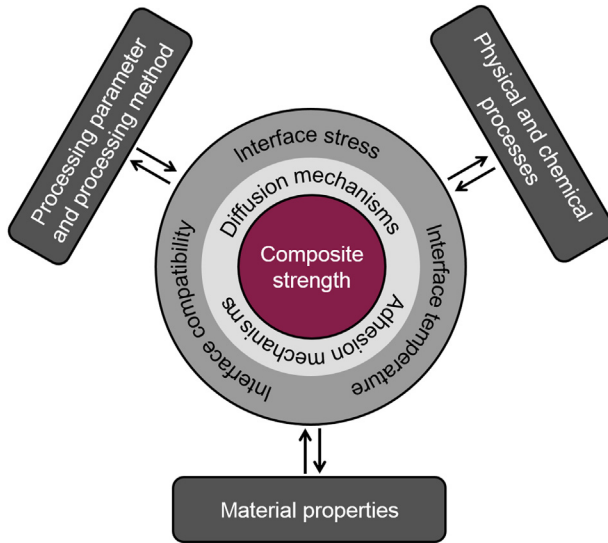


Figure 1.2 Influence factors of the bonding determinants that are relevant in practice.

1.4.1 Interface Compatibility

The term interface compatibility refers to the extent to which the material properties of composite partners promote, complicate, or prevent composite formation in the interface. The properties result mostly from a complex interaction of processing conditions, and thus they are rarely constant.

1.4.1.1 Surface and Interface Tension

The adhesion between two components is described by the Dupré equation, and depends upon the surface and interface tensions [2,12]. The equation describes the work needed to separate the components from one another.

The term surface tension refers to forces that take effect on the molecular level and aim to keep the surface of a liquid small. The surface energy specifies the amount of energy needed to break the chemical bonds when creating a new surface. In liquids, the surface tension equals the surface energy. In solid materials, this value can be measured only indirectly. The energy, or tension, determines the wettability and adhesion ability and is defined by the chemical structure of the materials [7]. It is based on the intermolecular interactions and various types of bonds [2]. The surface tension consists of a nonpolar, disperse portion and a polar portion [2]. The composite strength depends on both

portions [7]. The lower the difference between the surface tensions of both components meaning the closer the surface tension ratio is to 1, the better the composite strength [15]. However, there are exceptions—i.e., the insufficient bond strength of polyolefin combinations or PA6-PMMA combinations that can be explained by shrinkage discrepancies [1]. The polar portion of the surface tension can be increased by surface treatment. If the tension ratios strongly diverge, zero adhesion can occur. A prime example of where zero adhesion is specifically employed is assembly injection molding (see Section 1.5.1) [12].

The surface tension is also influenced by the process parameters, such as the temperature and the process-induced degree of crystallinity. As the temperature increases, the surface tension reduces. Thus, during processing (at high temperatures), lower stress values are on hand in a material than for room temperature [1]. Usually, the reduction of surface tension does not occur equally in both components, thus the ratio of the surface tension between the materials also differs during processing [1]. According to Ref. [1], the following equation enables an estimation of the surface tension ($\sigma_{(T)}$), in regards of the contact temperature. As a requirement the surface tension at start temperature ($\sigma_{(T_0)}$) and the specific volume of the polymer at start temperature ($v_{(T_0)}$) have to be known. The specific volume can be found in the p,v,T – diagram for the polymer. Furthermore the molecular weight of the polymer is assumed to be constant.

$$\sigma_{(T)} = \sigma_{(T_0)} * \left(\frac{v_{(T_0)}}{v_{(T)}} \right)^4. \quad (1.4)$$

Generally, crystalline phases display a higher surface tension than amorphous phases [1]. In plastic-plastic composites, for identical components, this can lead to varying values because the second component is in a melted (and thus an amorphous) state at the time of the contact. During the injection molding process, in this context, it is important to take into account that the first component possesses an amorphous surface layer owing to the rapid cooling conditions in these areas [1].

The term interface tension denotes the forces between two phases that are in contact, and is essentially defined by the surface tensions of the single phases. With regard to plastic-plastic composites, the lower the interface tension, the more adhesion and diffusion processes will be promoted [7,12]. When the same components are in contact, the interface tension is zero [12]. The interface tension is indirectly influenced by the surface tension, due to both material and processing parameters. Thus, additives, the molecular weight, the degree of crystallinity, and processing temperatures affect the interface tension [12].

1.4.1.2 Crystallinity

The crystallinity of a material strongly affects the molecular mobility, and, in the case of semicrystalline materials, has an essential influence on the composite strength. In extreme cases, this can lead to disadhesion, even in compatible materials [9]. The molecular chain mobility is limited in crystalline areas. As stated previously, a high molecular mobility facilitates diffusion processes. An increasing degree of crystallinity, whether material- or process-induced, counteracts the diffusion tendency, and, thus also the strength of the composite [16].

When injection molding semicrystalline plastics, a surface layer with a low degree of crystallinity, small crystallization nuclei, and spherulites is developed due to the rapid cooling of the mold. Reheating initiated by contact with the second component can cause the crystallization nuclei and spherulites to function as crystal nucleus and can result in a postcrystallization of the surface area. Similar effects have been observed for a later tempering process [6]. Should reheating occur, diffusion processes can take place if enough thermal input is available. This, in turn, promotes composite strength. If the thermal input from the second component is insufficient to melt the contact area, this can result in poor composite strength. This is due to diffusion processes being limited in the melt of the second component because it is injected beside postcrystallized areas and spherulites [12].

1.4.1.3 Molecular Weight

The influence of the molecular weight is characterized by two opposing effects. On the one hand, as the molecular weight increases, the molecular chain mobility decreases, which is particularly counterproductive for diffusion processes. On the other hand, the possibility to diffuse entire molecule tangles increases. The resulting, higher density of entanglements leads to increased composite strength. The optimal composite strength correlates with the molecular weight [6,12]. In general, a critical, minimum molecular weight exists. Below this minimum, the chains are too short for sufficient diffusion and entanglement processes, and, therefore, they cannot adequately contribute to the formation of the composite. The critical weight varies depending on the polymer [6]. The correlation of molecular weight and composite adhesion is displayed qualitatively in Figure 1.3.

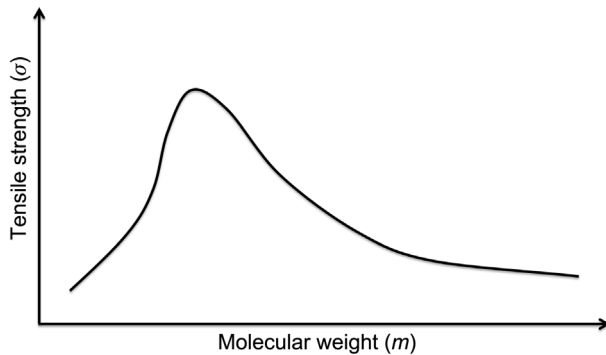


Figure 1.3 Qualitative influence of the molecular weight on the composite strength according to Ref. [12].

1.4.1.4 Polarity

The polarity has a decisive influence on the wetting. Good wetting is given if the polarities of the two components are identical [4,17]. Adhesion is not realizable if nonpolar and polar plastics are combined [6]. Functional groups at the surface (carboxyl, hydroxyl, and carbonyl groups) can help to achieve improved composite adhesion [8].

High polarity generally induces lower molecular mobility and thus inhibits diffusion processes. This, in turn, has a negative effect on the composite strength.

1.4.1.5 Molecular Orientations

The orientation of the molecules in the surface layer significantly influences the interface-transcending relaxation and diffusion abilities [4]. The orientation depends on the position in the flow cross section. Molecules in the outer layers are oriented parallel to the flow direction, molecules in the middle of the flow channel are less orientated in direction of the flow (Figure 1.4A). With regard to the composite formation, molecules that are oriented parallel to the interface can participate in the diffusion process at high temperatures, and, in doing so, contribute to enhancing adhesion. The higher the degree of orientation in the molecular chains, the larger the potential for elastic back deformation of the molecule, and, thus, the ability of chain segments to diffuse beyond the boundary layer. These correlations are shown in Figure 1.4B and C.

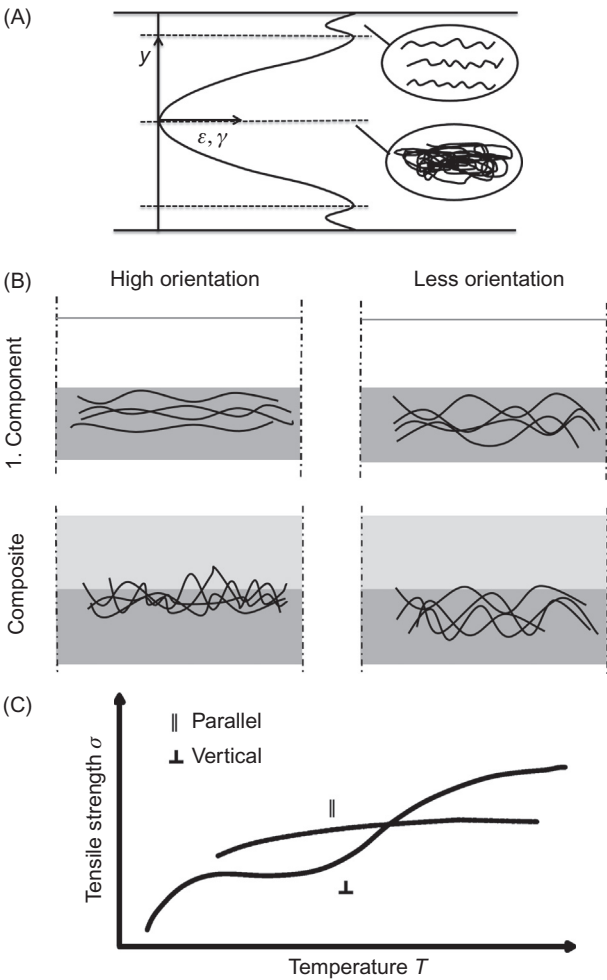


Figure 1.4 (A) Formation of orientations in the injection molding process, according to Ref. [4]; (B) Significance of orientations for diffusion, according to Ref. [4]; (C) Effects of orientations on the composite strength, according to Ref. [12].

1.4.1.6 Thermodynamic Compatibility/Miscibility

Thermodynamic compatibility or miscibility refers to the mutual penetration of molecules during diffusion processes [7]. The molecular mixing process is determined by thermodynamic processes (mixing enthalpy and mixing entropy) and influences the interface layer thickness.

Semicrystalline plastics are, in most cases, not capable of crystallizing together (isomorphic), making mixing only possible in the amorphous

areas. Here, the miscibility can be estimated in limited areas by means of the glass transition temperature. If complete miscibility is available, only one glass transition temperature will be measurable. However, if the materials are not compatible, differing glass transition temperatures of the individual components occur. [6,7]. Good miscibility promotes diffusion processes and positively affects the composite strength.

The solubility parameter describes miscibility as a prerequisite for diffusion processes. It is the square root of the cohesion energy density and is defined by secondary valence forces. If the parameters of both components range close to one another, a low mixing enthalpy is available and positively influences the miscibility and the composite strength. Strong, polar reciprocal effects (i.e., hydrogen bonds) complicate or prevent an accurate assessment of the mixing behavior by means of the solubility parameters. Surface pretreatment processes can also influence the solubility parameters [6,8,13].

1.4.1.7 Surface Pretreatment

The aim of a surface pretreatment is a fine cleaning or activation of the contact area to influence the surface and interface tensions. This should lead to adhesion improvement, with the purpose of increasing composite strength. Most often, it is used for material combinations with medium to zero adhesion, or to level out the effects of bad processing conditions. Owing to the additional means to influence the adhesion properties, processes with low temperatures or pressures can be used without losing adhesion. The most commonly used methods are adhesion modifications using primers, flaming, or corona/plasma methods. All these methods can be integrated into an injection molding process in normal, atmospheric conditions via handling systems or rotary disks [2]. For more information, please refer to the according literature [8,17–24].

1.4.2 Interface Temperature

The interface temperature and its chronological development are commonly viewed as the two most essential parameters of influence referred to composite formation by plastic-plastic composites. The temperature that results upon contact of both components fundamentally determines the formation of a boundary layer. The longer a higher interface temperature persists, the higher the degree of molecular mobility, and the higher the according tendency for diffusion processes will occur.

1.4.2.1 Mass Temperature/Injection Sequence

The required minimum interface temperature limit for a composite formation depends on the material. For example for polypropylene (PP), this temperature is defined at 130 °C. But for maximum composite strengths higher temperatures in the interface are necessary [9]. The melt temperature of the first component is, as a rule, unimportant, because often the first component has to be cooled down intensively to achieve stability in the molded part or dimensional precision. Insufficient cooling of the first component can lead to a deformation of the contact area due to the melt pressure of the second component [1]. If the first component is cooled down too much, zero adhesion can even occur in compatible materials if the heat input of the second component is too low [12].

The mass temperature of the second component should be selected in regards of its ability to melt the boundary layer of the other component. But, if the temperature selected is too high, for example by using another material, too much melting may occur, and cause deformation in the first component.

A contact temperature higher than glass transition temperature is recommended for a longer period of time for amorphous plastics. A contact temperature higher than crystallite melting temperature is suggested for semi-crystalline plastics. These temperature ranges enable a macro-Brownian mobility of the molecular chains, which is helpful for diffusion processes [9]. In regards of the thickness of the layer that needs to be melted to achieve good composite adhesion, literature suggests values between 10 nm and 10 μm [1,2]. This wide range can be explained by the fact that the amount of influence strongly depends on the materials and the material combination [6,9,12,13].

In composite injection molding, the interface temperature is influenced by several parameters. In addition to the temperatures of the components, the thermal diffusivity plays an essential role as well. It is defined by the density, the specific thermal capacity, and the thermal conductivity. The degree to which the melting temperature of the second component can be influenced is restricted, because it is material dependent, and cannot be varied to whichever desired degree. If the first component consists of a semi-crystalline plastic with a temperature that is lower than the crystallite melting temperature (T_C), a high amount of energy is needed to re-melt the crystalline areas. As a consequence, less energy is available to increase the interface temperature. This correlation can be seen in Figure 1.5.

Figure 1.6 provides an exemplary illustration of the temperature conditions in the interface of a butt joint. Here, two different interface

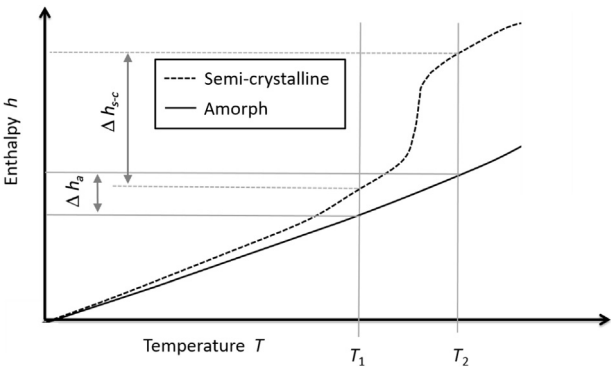


Figure 1.5 Qualitative trend of enthalpy by temperature for amorphous and semi-crystalline materials—for semi-crystalline materials applies: $T_1 < T_C$ and $T_2 > T_C$.

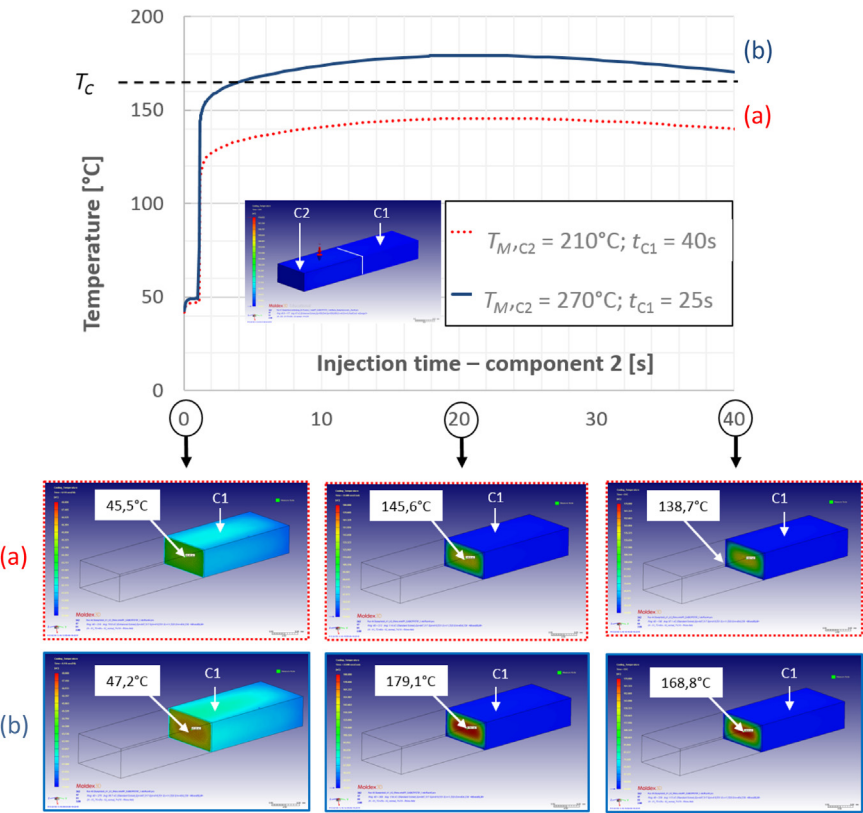


Figure 1.6 Temperature conditions in the interface for a combination of PP–PP; (a) melting temperature component 2 = low / cooling time component 1 = high; (b) melting temperature component 2 = high / cooling time component 1 = low.

temperatures are shown, resulting from two combinations of melting temperature of the second component and cooling time of the first component. Both components are of PP; the second component is directly injected after the end of cooling time (EOF) of the first component. The melt temperature of the first component was constant for both cases. In case (a) the melting temperature of the second component ($T_{M,C2}$) was set to 210 °C, which is the minimum suggested melting temperature for PP. The cooling time of the first component (t_{C1}) was set to 40 s. In case (b) the melting temperature of the second component ($T_{M,C2}$) was set to 270 °C, which is the maximum suggested melting temperature for PP. The cooling time of the first component (t_{C1}) was set to 25 s, which is the suggested cooling time for this part.

As can be seen in the graph, the resulting temperature in the interface of both components is for case (b) at a higher level and for case (a) at a lower level than crystallite melting temperature, for a long period of time. As also mentioned, the minimum required interface temperature of 130 °C for PP for composite formation is given for both cases, but for case (b) higher composite strength is expected.

The temperature in the interface is also influenced by the type of interface design. Figures 1.7 and 1.8 show the two, essentially different cases of a butt joint (1.7) and an overlapping joint (1.8).

In general the heat dissipation in the interface is lower than in direction to the mold wall.

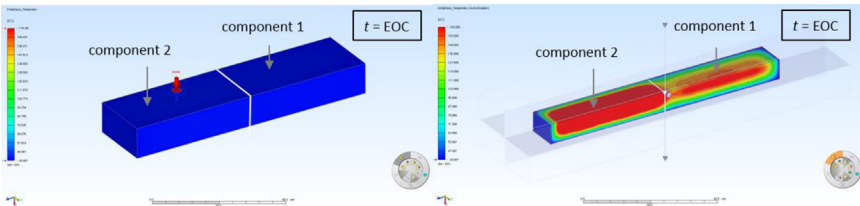


Figure 1.7 Temperature distribution in the interface of a butt joint connection—time in process = end of cooling (EOC)/ejection.

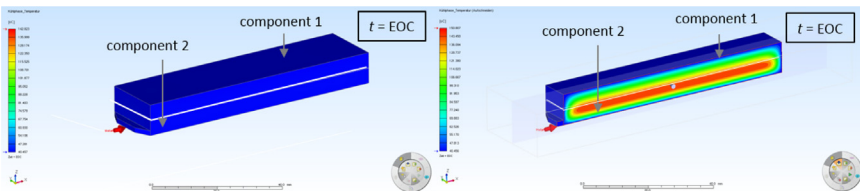


Figure 1.8 Temperature distribution in the interface of an overlapping connection—time in process = end of cooling (EOC)/ejection.

The heat dissipation in the interface is much lower than to the cooled mold wall. As a consequence, the temperature in the interface remains at a higher level for a longer period of time. Regarding the cross-sections, the temperature maximum is displaced toward the interface by the second component. For an overlapping joint, often, the interface area is larger, than for butt joints, thus more time at higher temperatures is on hand in the interface area.

1.4.2.2 Mold Temperature

The mold temperature significantly influences the interface temperature, crystallization, and shrinkage effects. It can have either positive or negative effects [2].

Generally, a high mold temperature results in improved wettability of the first component and a higher temperature level in the surface layer. Thus, it often leads to higher composite strength [1,13]. However, even low mold temperatures can promote diffusion processes for semicrystalline materials. The reason is, that for high cooling rates, less crystallinity in the surface layers is created [7].

1.4.2.3 Intermediate Cooling Time

In composite injection molding, the period of time between end of injection and holding pressure phase of the first component until injection of the second component is commonly referred to as the intermediate cooling time. Generally, a very short intermediate cooling time should be aimed for, in order to maintain the interface temperature at a high level.

In the research literature, there have been cases in which an intermediate cooling time that was too short contributed to poorer composite strengths and high distributions in strength. There is a time limit at which the highest composite strength can be achieved. Indirect factors of influence are suspected to be the reason—namely, the influence of shrinkage (in particular, short-term shrinkage), shrinkage-induced altered heat transfer, and crystallization processes which lead to shrinkage effects [9].

1.4.2.4 Contact Time

Provided that a sufficient joining force is available, a time limit exists in which the composite formation can be influenced positively. Above this time limit higher contact times show no additional effects. A higher thermal input leads to an accelerated diffusion, and, thus, can lead to comparable strengths within shorter times and increased achievable strength values [6,12]. The qualitative correlation can be seen in Figure 1.9.

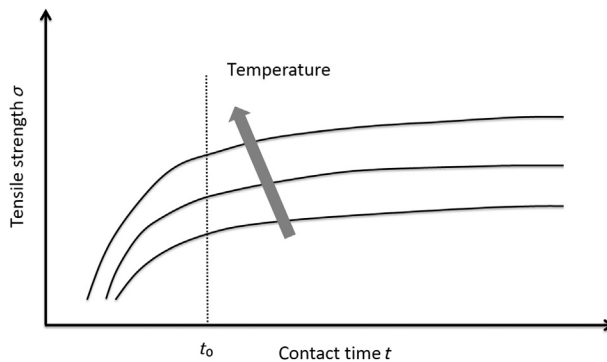


Figure 1.9 Composite strength in correlation with the contact time and the interface temperature according to Ref. [12].

1.4.3 Interface Stresses

Tensions in the interface can be triggered by countless factors. They can be process induced, or, at a later point in time, they can be triggered into stress states by various properties of the joined components when in use (i.e., heat expansion, differences in E moduli, and different shrinkage values). Tensions can negatively influence the composite strength to a large extent.

1.4.3.1 Shrinkage

Shrinkage is caused by processing of material. There are three types: demolding shrinkage, processing shrinkage, and postshrinkage. Demolding shrinkage refers to molded part deviations that occur directly after the demolding process. Processing shrinkage is defined as the shrinkage effect that takes place 16 h after manufacture. All later shrinkage effects (i.e., relaxation of internal stresses, reorientation processes, and postcrystallization) are called postshrinkage, and are not categorized over a specific time period (Figure 1.10). Shrinkage can be influenced by numerous processing parameters, especially in the case of semicrystalline plastics. In plastic-plastic composites, all shrinkage proportions can take effect depending on the type of process control.

Differing shrinkage behavior of various components can lead to stresses in the interface. Here, shrinkage that takes place perpendicular to the connection area can be critical and negative in regard to the composite strength [7]. However, process-induced and geometry-induced stresses can also occur in identical components. For instance, the higher temperature of the second component can lead to different processing shrinkages upon coming into contact with the much cooler first component, thus, creating stresses.

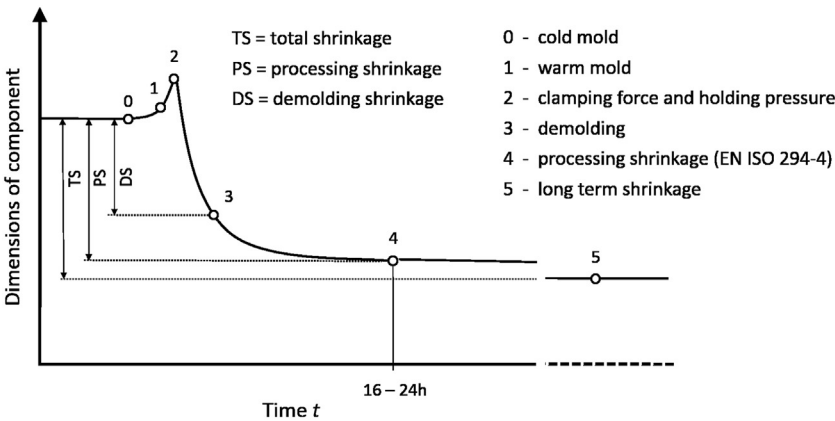


Figure 1.10 Chronological sequence of shrinkage, according to [9].

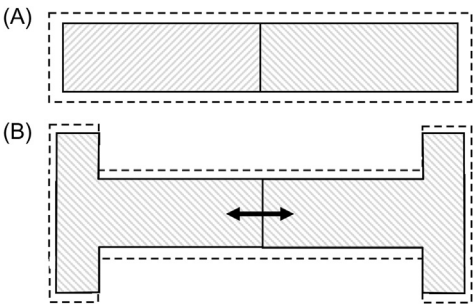


Figure 1.11 Formation of shrinkage in butt joints and overlapping joints: (A) free shrinkage and (B) form bound shrinkage.

At the moment that the melt of the second component comes into contact with the first component, the shrinkage phenomena begins and influences composite formation. The geometry of the joining zone and of the component itself has a major influence in this context. In this regard, a differentiation is made between free shrinkage and form bound shrinkage. Components can shrink in all directions when free shrinkage is taking place. Form bound shrinkage refers to the restriction in the shape of the cavity, which is predefined by the sprue, undercut, ribs, and connecting parts, and influences the shrinkage. If the direction of shrinkage leads away from the interface, the form bound shrinkage can initiate higher tensions in the interface, and, therefore, it can cause poorer composite adhesion [7]. The influence of the shrinkage in dependency of the type of joint can be seen in Figure 1.11.

1.4.3.2 Connection Design/Interface Geometry

The type of connection design offers many possibilities for influencing the composite strength. Interlocking connections (e.g., undercuts or perforations) mechanically support the composite strength [2]. Depending on the sprue position and interface geometry, it can be distinguished between butt and overlapping joint [12]. The joint design affects the molecular orientations in the interface (see [Section 1.4.1.5](#)). Molecules oriented parallel to the interface can participate in the diffusion process at higher temperatures, and contribute to enhancing adhesion. Diffusion processes can take place as a consequence of the first component melting due to the heat input of the second component. In butt joint connections the melt of the second component contacts the whole interface area approximately at the same time. In overlapping connections, an overflowing occurs, which leads to different temperature and pressure conditions in the connection area. This can lead to local differences in adhesion. Furthermore an overflow leads to wall-sticking at the first component which affects the molecule orientation [12]. In most cases, the implementation is done stepwise, shafted, or butt, and can result in varying results for the according material combinations [6]. Therefore, a general statement cannot be made concerning the influence.

In addition to interlocking connections, a form fit is usually included in practice [2]. A form-fitted version is the most reliable option, even if it is more costly due to the need for a more complex mold. Moreover, the difference in modulus and the elasticity of the materials must also be taken into account. Differing deformation behavior in components can lead to a separation of the materials when load is applied.

1.4.3.3 Surface Roughness

There is the option of roughening the contact surface. One example of this would be molding the first component on a rough surface of the slider, which opens the volume for the second component [12]. This essentially enhances adhesion due to the larger contact surface, but is also connected to negative factors of influence. High levels of roughness can inhibit the wettability and enable air or dirt to enter the contact area [1,4,17]. A complicated penetration of the melt can lead to stress peaks in the interface [6]. Moreover, the larger composite surface can result in greater heat dissipation, which, in turn leads to a lower heat level in the contact area. However, in most cases, the influence of the

roughness is much lower than the influence of process control and should be assessed depending on the material [1,9].

1.4.3.4 Mold Design

The mold design can significantly affect the processing conditions. Flow path, flow cross section, and the direction of the inflow define the local melt front speed, flow, and cooling conditions. In turn, these factors affect the compression ratio and temperature conditions, and thus also the viscosity. In addition, the sprue type and position play an important role. In the end, these factors influence the relaxation, orientation, and mobility of the molecular chains.

For this reason, it is difficult to make general statements about the influence of the mold design on the composite strength. Due to the large number of influencing factors, the processing of identical plastics in different molds can result in differing composite strengths [2].

In general, of course, the elimination of air is recommended in the contact area in order to counteract air pockets. Furthermore, thinner wall thicknesses in semicrystalline materials prove to be mostly beneficial with regard to the composite strength. This effect is supposed to be a consequence of the lower crystallinity of the first component induced by faster cooling [7].

The local pressure and temperature conditions vary in the component. Thus, the length of the flow path also has great significance for the composite strength. For a good adhesion, the temperature in the boundary area, the pressure, and the time of contact are recommended to be high. These conditions can normally be realized more easily near the gate, but they also strongly depend on the component geometry. Experiments have shown that the longer the flow path, the greater the composite strength. This is due to the so-called pressure delay time—meaning the time between wetting and building up pressure. This time decreases throughout the length of the flow path. At the end of the flow path, the pressure increase takes effect directly after wetting, which is beneficial for the composite strength. Near the gate a solidified surface layer can be developed, which is pressed on the first component with low pressure — at the beginning of the injection phase only the filling pressure. The pressure increase that occurs later, after the mold has been completely filled, does not have as much effect near the gate because the molecular mobility is already restricted in this area. But also, frontal injection attempts have shown that the composite strength is not determined by the pressure delay time alone [2,6,12,25].

1.4.3.5 Thermal Expansion Behavior

Varying degrees of thermal expansion in the components can lead to tensions in the interface that are mostly larger than flow-induced stresses. In hard-soft combinations in particular, expansion inhibition can occur in the surface area of the soft component because of the fixed connection to the hard component; thus, stresses can be induced [2].

Stresses negatively affect the composite adhesion. Similar heat contractions in both components are optimal, meaning, the closer the ratio of the thermal expansion coefficients of both applied materials is to 1, the better [7,15].

1.4.3.6 Injection and Holding Pressure

The processing pressures affect the wetting behavior, the molecular convergence, and the molecular orientation, and thus, the diffusion processes in particular.

The diffusion process itself is not dependent on the pressure [12]. Even though a higher composite strength is observable up to a certain pressure level, it can be traced to a reduction of cleavings between the joining partners [12]. The influence of the holding pressure is often regarded as subordinate in the literature [e.g., 1,2,8,12,13,25]. The effective direction of the holding pressure's influence is connected to the material combination and the injection sequence. It can be either positive or negative and is usually only measurable to a limited pressure value. Once this level of pressure has been reached or passed, macroscopically there is complete contact and a sufficient convergence for diffusion processes for both components [6,9].

The pressure-time-sequence of the holding pressure determines the shrinkage to a great extent. In this regard, a difference is observable concerning whether low pressure was applied for a long time, or a high pressure applied in a short period. Constant pressure loses influence over time due to continuing cooling. If the pressure is too high, molecular stretching, deformations in the contact surface, and local shrinkage and stiffness differences can result. They, in turn, negatively affect bonding strength [1,9].

1.4.3.7 Injection Speed

The injection speed essentially determines the degree of molecular orientation and, thus, affects the adhesion, orientation, and shrinkage [2].

With regard to the composite strength, also both positive and negative effects are possible [2]. A higher shear heating (higher mass temperature) and shorter pressure delay time that correlate with high injection speeds can increase composite strength [4,6,13]. At the same time, it is also possible for a higher molecular orientation to cause shrinkage-induced stress in the contact area, which, in turn, can inhibit bonding [2].

Due to the influence of the holding pressure, the effects of the injection speed are assessed in correlation with the material combination and further boundary conditions in differing ways in the literature [9]. While several investigations did not identify any significant influence [4], others observed a semiimportance of the composite strength at a greater injection speed [8,25]. However, it is crucial to note that in some material combinations, an influence was verified only in combination with high mass temperatures.

1.5 Machines and Processes

Having extensively elaborated the fundamental effects that play a role when manufacturing plastic-plastic composites using injection molding in the previous sections 1.2–1.4, this section now puts these effects into a practical context. Numerous, special injection molding techniques exist for the manufacturing of plastic-plastic composites. An attempt to structure these techniques often proves to be difficult. In most cases, a clear definition of processing terminology is missing, meaning the terminology used varies and can denote different processes depending upon the provider or sector. Moreover, it is also common that varying terminologies are used for nearly identical methods. This is often the case when several providers market similar methods with differing names. Due to overlapping with regard to content, establishing a hierarchical structure is complicated. Consequently, the existing approaches concerning this matter have resulted in varying outcomes [26–29].

This chapter has a different type of structure in an attempt to avoid this problem. Manufacturing methods for plastic-plastic composites can be distinguished by means of four criteria, which comprise the employed material combination, the point on which the components are combined, the chronological sequence, and the material and handling technologies utilized. Each special technique can be described as a combination of characteristics of these criteria. If you employ a morphological box, each special technique represents a path through the box. Figure 1.12 emphasizes this relationship and provides an example for the monosandwich method which is highlighted by the boxes with a dark background.

Criteria	Realization							
1. Material combination	Compatible materials					Incompatible materials		
2. Point of material joining	Dosage unit		Barrel in front of the screw		Runner system		Cavity	
3. Injection sequence	Sequential					Simultaneous		
4. Tool technologies	Standard tooling technology	Slider technology	Transfer technology	Rotary disk	Index plate	Linear tooling systems	Horizontal turning technologies	

Figure 1.12 Morphological box to distinguish special molding techniques for plastic-plastic composites.

In the ensuing section, these four criteria mentioned in [Figure 1.12](#) are introduced and their correlating parameters and effects are explained. In some cases, specific special methods are used as examples.

1.5.1 Material Combination—The Example of Assembly Injection Molding

The question of whether plastics of the same type are combined with one another, or whether two differing material types are combined, not only influences the later molded part properties (warpage, orientations in the interface, etc.), but also the process design. Materials are classified as the same type when they consist of the same basic material and do not contain any additives that can alter their properties strongly.

When combining identical materials, a good interface compatibility can generally be assumed because the parameters of significance for adhesion (i.e., solubility and polarity) are high, and the interfacial free energy equals zero (see [Section 1.4.1](#)).

By combining different materials, these conditions are not fulfilled automatically. The ratio of the surface stresses, as well as parameters such as the solubility and polarity, must be taken into account for each material pairing. Moreover, it is important to keep in mind that differing shrinkage behavior can promote the creation of interface stresses (see [Section 1.4.3](#)). This also can occur when employing the same materials with differing filling contents, or when there are greater temperature differences between the individual components (see [Section 1.4.3](#)).

In addition to a theoretical observation, practical results can also be employed. It is crucial to note that the created compatibility tables are not

	ABS	ASA	CA	EVA	PA 6	PA 6.6	PBT	PBT/P	PC	PC/ABS	PC/PBT	PC/PBT/P	PC-PET	PE-HD	PE-LD	PET	PET/P	PMMA	POM	PP	PPO	PS	PS-HI	PSU	PVC-H	PVC-W	SAN
ABS	3																										
ASA	3	3																									
CA	3	3	3																								
EVA	3	3	0-1	3																							
PA 6	2-3	2-3			3																						
PA 6.6	2-3	2-3			2-3	3																					
PBT	3	3	3				3	3																			
PBT/P	2-3	2-3	2-3		2-3	2		3																			
PC	2-3	2-3			2-3	1	2-3	2-3	3																		
PC/ABS	3	3			2-3	2-3	2-3	3	3																		
PC/PBT	2-3	2-3			2-3	2		2	2-3	2	3																
PC/PBT/P	3	3			3	3		3	3			3															
PC-PET	2	2			2	2		2	2	2	2		3														
PE-HD	1	1	1	3	1	1-2	0	1-2	1-2	1	1	1		2-3													
PE-LD	1	1	1	3	1	1-2	0	1-2	1-2	1	1	1		3	3												
PET	3															1											
PET/P	2-3	2-3						2-3	2-3	3	2	3	2	0-1	1		3										
PMMA	2-3	2-3						1	1	2-3	2-3	3	2	0-1	1		1	3									
POM	1-2	1	0-1		1	1		1	1	1	1	1	1	0-1	1	2	1-2										
PP	1	1	1	3	0-1	1	0	1-2	1-2	1-2	0-1	1	0	1-2	3			0-1	1	2-3							
PPO	1	1	1		0-1	0-1	0	1	1	0-1	1	1		1	1		1	0-1	1	1	3						
PS	1	1	1	3	1	1	0	1-2	1	1-2	0-1	1	0	1-2	1		1	1	1-2	1	3	3					
PS-HI	1	1-2	1-2	2-3	1-2	1-2	0	1-2	1-2	1	0-1	1	0	1-2	1-2		1	1-2	1-2	1-2	3	3	3				
PSU	3	3						3	3	2-3		3		1	1		3			1	1	1-2	1-2	3			
PVC-H	3	3																3		2	2	2		3			
PVC-W	2-3	3	3	3	1-2			3	3	3	3	3		1-2	1-2		3		1-2	1-2	1-2	1-2		3	3		
SAN	3	3	3	3	3	2-3	3	3	2-3	3	2-3	2-3	3	1	1	1-2	3		3	1-2	1-2	1	1	1-2		3	3

0 = no adhesion
1 = poor adhesion
2 = good adhesion
3 = very good adhesion

0 = no adhesion
 1 = poor adhesion
 2 = good adhesion
 3 = very good adhesion

Figure 1.13 Adhesion compatibility of various material combinations for orientation purposes [2,8,16,26–28,30–33].

based on experiments that were carried out using standardized conditions. Therefore, they can be utilized only for reference purposes. Also, the high dependency of the composite adhesion on processing and geometrical parameters also puts the informative value of such compilations into perspective. Nevertheless, Figure 1.13 depicts a summary of several diagrams for orientation purposes.

However, substance-to-substance bonded connection is not always the goal of this process. Assembly injection molding aims for something that connects the components but it does not fixate them; thus, the components are still allowed to move against one another. Depending on the application, friction between the assembled parts is specifically desired, or else to be avoided. Typical reasons for utilizing assembly injection molding include the reduction of the number of assembly processes, the creation of permanent bonds, the manufacture of bonds that cannot be assembled using a conventional strategy, the achievement of closer tolerances, or the creation of abradant connections, such as friction or sliding clutches [34]. An incompatibility of the joining partners in accordance with the previously observed aspects is beneficial in this context. Nevertheless, combinations of identical plastics (meaning those with an essentially high interface compatibility) can be joined with one another by means of assembly injection molding if the shrinkage effects are specifically utilized.

In the case of such composites, short-term shrinkage plays a decisive role. Depending on the material or processing method, this can represent a large proportion of the processing shrinkage. On average, design engineers can expect short-term shrinkage of approximately 40%. However, this value can range between 15% and 60%. A reduction of short-term shrinkage can primarily be achieved by increasing the holding pressure, the tool temperature and the wall thickness. In addition, a longer holding pressure time, a shorter cooling time, or an increased mass temperature can make a minimal contribution to the reduction [35].

Regardless of the compatibility of the joining partners, melting and deformation of the components first injection molded should be avoided by selecting a moderate pressure and temperature level [36,37]. Often, a material with a higher melting temperature is used for the premolded part in order to guarantee that the processing window for the completion of the second injection process remains relatively wide [36].

1.5.2 Point of Material Joining

When manufacturing composites using injection molding, there are various methods to choose from for combining the materials. The most commonly used method is a joining of the components in the injection molding tool. Joining can also be completed in the nozzle, in the barrel in front of the screws, or when feeding in the material. In the next sections, these four methods will be illustrated with examples.

1.5.2.1 *Joining Materials in the Tool—The Example of Bi-injection*

For this method of joining, the availability of several injection units or the insertion of premolded parts is a prerequisite. In this case, primarily sequential processes are available (see [Section 1.5.3](#)). Bi-injection technology represents an exception. When employing bi-injection, two melts from two different injection units are simultaneously injected into the tool via two separate sprues. [Figure 1.14](#) illustrates this.

The interface that develops during the joining of the materials, even if it is fairly repeatable, cannot be clearly defined with regard to its contour. Merely a relocation is possible when adjusting the injection speeds of the single units. There are two crucial reasons that this method is selected. The first was that it is a simple process, with low tool costs. For this reason, it is used for applications with low optical requirements regarding the weld line. An example of such an application consists of illuminated multicolor icon switches in the automobile industry.

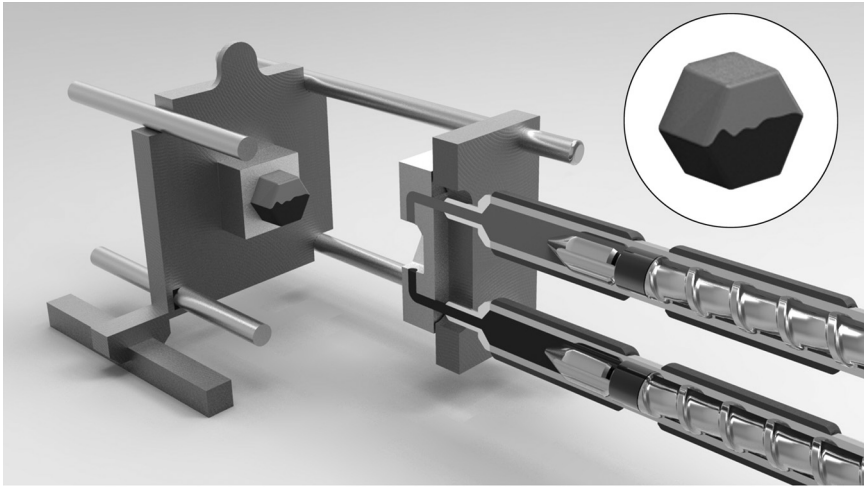


Figure 1.14 Bi-injection technology.

The second reason that this method is selected is because it enables a perfusion of the weld line by means of precise control of the injection and holding pressure processes. In particular, the special case of push-pull injection molding aims to do this. Here, a multiple perforation of the weld line is achieved by alternating injection [9,38].

Owing to the extremely high interface temperature in these processes, excellent composite adhesion can be achieved (see [Section 1.4.2](#)). Especially when using push-pull injection molding, it is possible to completely remove the orientations in the weld line. This factor, in combination with similar temperature levels of the melts, usually leads to low interface stress (see [Section 1.4.2](#)). In most cases, primarily identical materials are processed, which usually just differ in color. In this scenario, a high interface compatibility can be expected (see [Section 1.4.3](#)).

All other methods that join the materials in the tool consist of a sequential injection of the components. As a consequence, a lower interface temperature results. It is possible for melting to occur in the interface due to the material and processing parameters, however, it is not sufficient to significantly alter the orientations in the interface. Also, due to the larger temperature differences, the interface stresses are greater.

1.5.2.2 Joining the Materials in the Nozzle or in the Barrel in Front of the Screws—The Sandwich Technique

When materials are joined in the tool, there are several injection points. However, when the materials are combined in the nozzle, all materials are

inserted into the tool via the same runner. As a consequence, the rheological parameters have a greater significance during the formation of the composite. The interface factors described in [Sections 1.4.1–1.4.3](#) are still present, but, in relation, their relevance is less. Parameters such as the quality of the interface and the volume ratio of the individual components gain in significance with regard to the component.

The most important example of a combination of the melt in this manner is the sandwich method. Like the monosandwich method, it aims to create a multilayered structure. Both methods are classified as co-injection [\[27\]](#). [Figure 1.15](#) shows the differences found in the processing sequence.

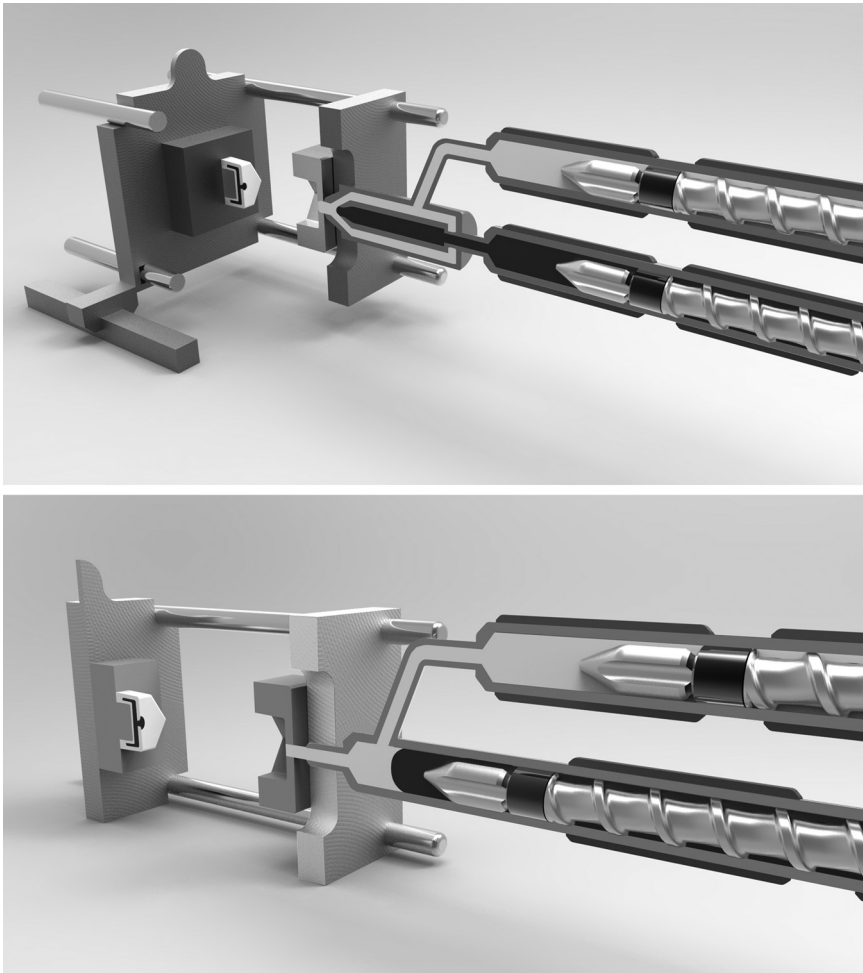


Figure 1.15 Traditional sandwich technique (top) and monosandwich technique (bottom).

Due to the similarity of both versions of the sandwich method, several aspects that are valid for both methods will be elaborated. Subsequently, a differential observation of the method variants will be carried out.

1.5.2.2.1 Sandwich Technique—General Information

The multilayered structure comprises a skin component situated on the component surface, and a core component surrounded by it. The utilization of such methods is beneficial for several reasons. A material with a low density or a foamed material can be used for the core component in order to achieve a lower weight. For wall thicknesses larger than 4 mm, foaming is also useful to prevent sink marks [2]. If recycled material is used as the core component, financial benefits result from utilizing this method [2,15]. Furthermore, the combination of a fiber-reinforced core material, with good mechanical properties, and an unreinforced skin material, with better surface and optical properties, is commonly used. Also, another potential of the sandwich method is the achievement of specific technical functions by means of purposefully combining materials with different properties [15,39].

The general prerequisite for composites is an interface compatibility between the skin and core material (see [Section 1.4.1](#)) [15], and a composite compatibility with regard to shrinkage and stiffness (see [Section 1.4.3](#)) [29]. The materials selected for the skin and core components and their volumes crucially influence the properties of the composites. For example, in the case of a combination of Polyamid 6 as the core material and polybutylene terephthalate filled with 20% glass fiber as the skin material with a larger core ratio, the flexural modulus and strength increase, while the impact strength goes down [40]. Accordingly, the adjustment of the ratio between the skin and core material must be devoted a high amount of attention. Decisive factors include the method of injection, the position of the sprue, and the design of the molded parts [2]. In contrast, the processing parameters are far less important [2].

The quality of the layered structure (more precisely, the precision in the layer's uniform thickness) is primarily determined by the viscosity of the components due to the sequence of processing. During the injection of the second component, a laminar flow is induced [39,41]. In order to prevent flow instabilities, the ratio of the shearing viscosities of the core to the skin material should range between 0.5 and 5 [2,29]. If the ratio is lower, ruptures occur; if it is higher, poorer filling behavior and a varying wall thickness distribution results [40].

A core material with a low viscosity changes direction slightly when faced with varying flow resistances. Thus, preferred flow paths are created, and, simultaneously, displacement no longer takes place in some areas. This effect, which is subject to self-enhancing, is referred to as the finger effect [26]. An observation of selective table values of viscosity is insufficient in predicting this effect, as the viscosity varies indirectly through time and local variables, or also through direct shear and temperature properties [29].

As was the case for the ratio between the skin and core, the mold geometry also plays an essential role concerning the quality of the layered structure. Rotationally symmetric mold parts are especially suitable for sandwich applications. The larger the divergence in the mold part design, the higher the probability that inhomogeneities will arise, and, in turn, the lower the ratio of the core material will be [2,39].

1.5.2.2.2 The Basic Sandwich Method

The regular sandwich method involves a joining of the skin and core material in the nozzle. Small injection weights can be integrated on standard machines by means of using a sandwich adapter plate, which is mounted on the side of the nozzle between the clamping platen and the tool [26]. In the case of larger components, or strongly differing injection weights for individual components, hot runner co-injection heads are employed [42]. The injection units are usually situated next to each other or on top of one another [26,42].

It is possible to employ both cold and hot runners. In the case of hot runners, a special manifold replaces the injection head [27]. Special nozzles are employed to control the melt flow of the skin and core components. They are characterized by separate valves for the individual components [26]. With regard to the mold itself, specific adjustments are not necessary [27].

Employing two separate injection units enables the precise control of the injection sequence. This sequence consists of three phases. In the first one, the skin material is injected, followed by the core material in the second phase. If sealing the gate is necessary, due to visual requirements, the third phase completes the sequence with another injection of the core material. Otherwise, the core material is used to compensate shrinkage in the third step. Usually, a simultaneous phase in which the skin and core material are injected at the same time is included between the steps to avoid abrupt changes in flow velocity and resulting flow marks [26,27,42].

1.5.2.2.3 Monosandwich Method

The monosandwich method specifically combines the materials in the barrel in front of the screw. An extruder that directs one of the components into an injection unit from the side is required. It is connected via a force-controlled, three-way valve [43]. As can be seen in Figure 1.13, the actual injection process is carried out by only one unit, meaning that switching between the units during the injection sequence is not necessary [43]. This, on the one hand, simplifies process control; but on the other hand, it simultaneously reduces the possibilities to influence the process. In order to prevent ruptures, the core content or injection speed may have to be reduced [40].

Here, the nozzle technique is less complex than in the regular sandwich method because it must be designed for only one melt flow [2,43]. The achievable ratio of core material is comparable to that found in regular sandwich injection molding, and it equals approximately 60% [39]. It is possible to use standard tools; however, it is not possible to use hot runners with a simple needle valve due to the mixing effect that occurs [2,15,44]. Also, a sprue sealing cannot be accomplished by injection of the skin material when using the monosandwich method [39,45].

1.5.2.3 Combining Materials via the Material Feed—The Marbling Technique

In the previously discussed methods of joining, at least one of the components was in a molten state. Here, however, the materials are partially combined in a solid state, as can be seen in Figure 1.16. Even if the according methods are categorized into reproducible and nonreproducible variations [26], the mixing (and thus the appearance of the part as well) are subject to stochastic fluctuation.

Nonreproducible effects are primarily categorized under the term “marbling”. Here, similar (but not identical) optical effects are aimed for in the components. These can be achieved by means of an inhomogeneous color distribution, or by combining different materials [26]. The materials should not be allowed to dissolve completely into one another (see Section 1.4.1.6). In particular, material combinations that possess the required interface compatibility for adhesion (see Section 1.4.1) but differ with regard to their melting behavior are highly suitable [26]. The lowest degrees of mixing are achieved by employing plunger injection units [26].

Reproducible variants display specific analogies to the monosandwich method. They can be achieved either by employing a complex

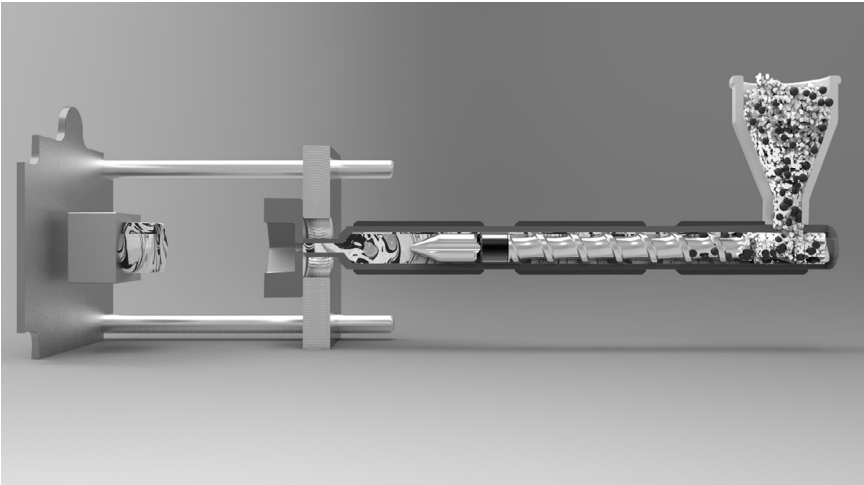


Figure 1.16 Marbling via the material feed.

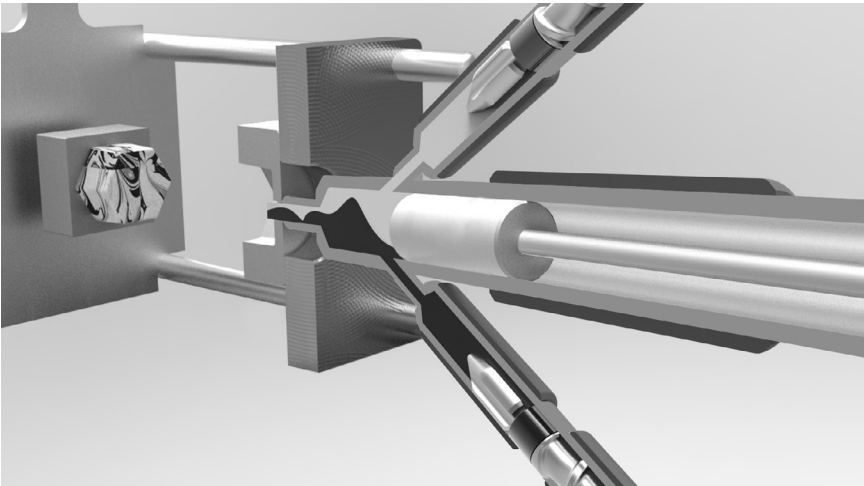


Figure 1.17 Marbling technology based on the loading of a plunger injection unit.

nozzle technique in a sequential injection, comparable to the regular sandwich method [26], or by the monosandwich method by loading a plunger injection unit in layers [26]. The latter technique is illustrated in [Figure 1.17](#).

The close relation between the method's variables is clear when it comes to the Admix method. It is used to create sandwich structures and does not require additional plasticization units. Special dosing units alternating feed granulate of the core and skin material starting and ending

with the skin component. As a result a layered structure of melts is generated in the barrel in front of the screw. However, achievable core-skin ratios are lower than in the case of the classic sandwich technique [26]. All marbling technologies can be carried out on conventional cold runner tools and do not require special tool modifications [46].

1.5.3 Injection Sequence

The chronological order of the injection processes strongly influences the later properties of the components. First and foremost, a differentiation can be made between simultaneous injection and sequential injection sequences. The time between each injection process is the decisive factor. When injecting in a successive circuit, as shown in the sandwich-molding process, the time between each sequence equals almost zero. Breaks that last several seconds (common in many rotational tool concepts), or up to several days (insertion technique) are possible. In several specific cases (i.e., sandwich injection molding), a mixed form is formally available. This is because both simultaneous and sequential injection are parts of the cycle. In the next section, the effects of various orders on the adhesion in the composites will be elaborated.

1.5.3.1 Simultaneous Process Control

Simultaneous process control implies that the viscosities and the temperatures of the components are on comparable levels at the moment the materials come into contact. Often, an interface temperature sufficient for diffusion processes is available (see [Section 1.4.2](#)). In addition, depending upon the process control, a penetration of the melts in the contact area can occur. This can cause an enlargement of the effect contact area, but also a reduction of the surface stress differences of the flow front (see [Section 1.4.3](#)). The orientations in the material that are otherwise mainly parallel to the interface, especially in fiber-filled materials, do not develop as well when melts collide. Thus, this phenomenon, also allocated to surface compatibility (see [Section 1.4.1](#)), can positively influence composite adhesion.

If the difference in temperature between the components is low, the shrinkage-based interface stresses are merely based upon deviations in the heat expansion of the materials (see [Section 1.4.3](#)). Therefore, they are lower than in sequential process control.

1.5.3.2 Sequential Process Control

If one component is injected and then another injected after that, then it can be assumed that the available interface temperatures are less than those found in simultaneous process control. However, this does not imply that diffusion processes across the interface are impossible. The prerequisite here is achieving the necessary temperature limit on the surface of the component injected first (see [Section 1.4.2](#)). A very short period between injection of the first component and contact with the second is beneficial (see [Section 1.4.2](#)). Moreover, differences in the processing temperatures of the materials can be specifically utilized. For this purpose, the material with the lower melting temperature should be used as the first component. The manufacture of hard-soft components is an exception because deformations of thermoplastic elastomer (TPE), which usually melts at a lower temperature, inhibit its use as a first component. If it is not possible to achieve interface temperatures higher than the temperature limit for diffusion processes of the first component due to processing (i.e., in insertion processes), adhesion processes gain significance (see [Section 1.3.1](#)).

1.5.4 Tool Technologies

Different injection molding tool concepts are available in practice which can be used to manufacture plastic-plastic composites. However, no clearly defined, standardized classification exists. Various attempts to classify [e.g., [4,6,8,46,47](#)] utilize similar criteria to differentiate between the tool technologies. Therefore, the technologies are distinguished, based on whether the preformed piece, which was made in the first injection process, remains in its current position in the tool or is repositioned. In the case of the latter, a differentiation can also be made between the types of repositioning. Repositioning can be achieved by either using handling machines or moving the tool, which can have either a rotational or linear design. [Figure 1.18](#) shows an outline of the classifications mentioned here. Implemented tool technologies have been used as examples.

1.5.4.1 Slider Technology

This tool technology is often referred to as the core back technique in accordance with the method associated with it. The process starts with the injection of the first component. After a short cooling period,

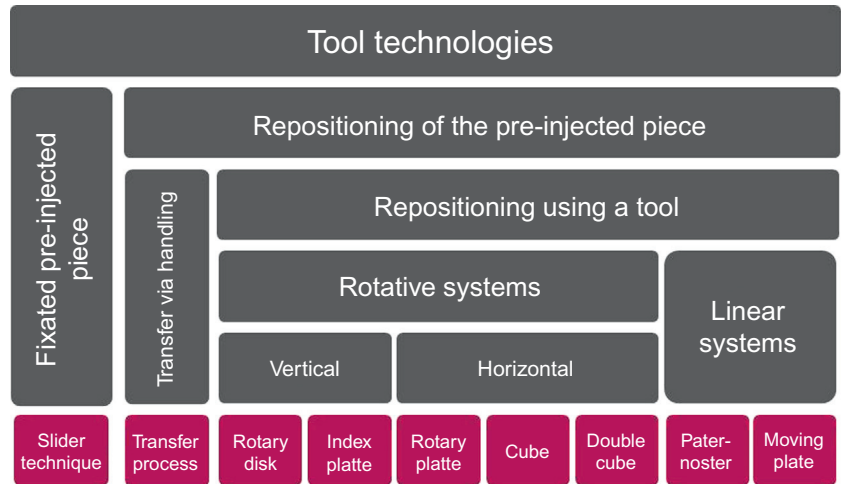


Figure 1.18 Classification of tool technologies.

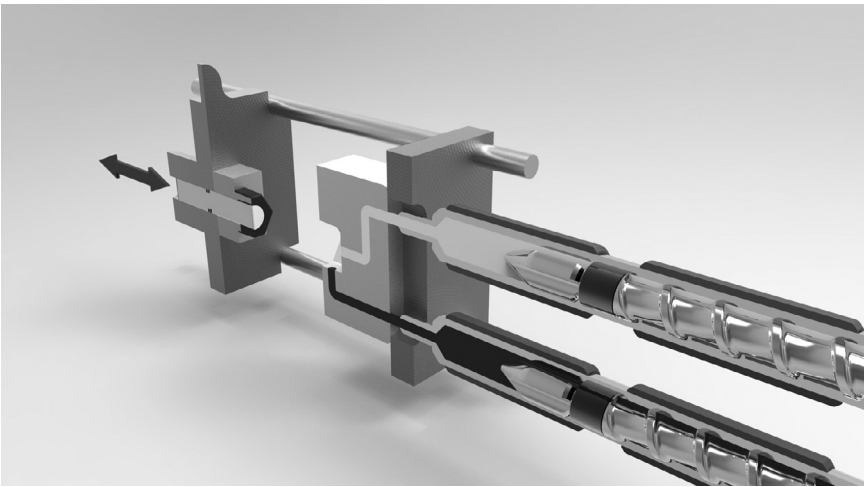


Figure 1.19 Core back technique.

the cavity volume is enhanced for the second component by means of a core or slider. [Figure 1.19](#) depicts this principle.

Tools based on this concept often have a very simple design [\[46\]](#). Consequently, their structure is compact, which, in turn, enables an effective utilization of the available construction space [\[42\]](#). Moreover, the investment costs are low in comparison to that of the methods that will be introduced later in this chapter [\[7,30,42\]](#). The simple design also has disadvantages though. The point of injection can be chosen flexibly

[46], but the cavity design on the ejection side is highly restricted because additional space must be provided by means of an axial movement. In certain cases of application, a slider must be applied on the nozzle side [48]. Complex geometries can be achieved using collapsible cores; however, this is usually not the best method from an economic perspective [6].

The cycle times that can be accomplished with slider tools are longer than for rotating tools. Even though a cavity opening between the injection of the first and second components can be discarded [26,46], the sequential process requires more time for the injection of successively injected units [6,7,46,48] than simultaneous injection processes in other methods. Due to the low tool cost, but higher cycle time, this method is primarily used for small series [48]. With regard to composite adhesion, slider tools prove to have advantages that repositioning technologies do not. Owing to the quick succession of the injection steps, the preinjected piece does not cool off as much, and higher interface temperatures are achieved (see Section 1.4.2) [6,46]. Also, with regard to interface stresses, better conditions are to be expected.

1.5.4.2 Transfer Process

The transfer process consists of moving the preinjected piece into a second cavity by means of a handling machine. Two types of transfer are distinguished. In the case of relocating, the preinjected piece is moved from one cavity to the next within the tool [48]. The cavities can be either above one another or next to each other [46]. In the case of the insertion technique, the transfer is carried out between two injection molding machines [48]. The difference between both variations is illustrated in Figure 1.20.

Analogous to the slider technology, tools that employ transfer technologies in general require a simpler tool design than that of rotating or linear alternatives. Moreover, the compact structure enables good utilization of the available clamping surface [48]. The insertion technique, the transfer between two machines, also enables an efficient utilization of the clamping force [46]. The possibility to position the cavity in the center of the tool [4], as well as the potential to adapt the size of each injection molding machine to the injection process realized on it, have positive effects. Repositioning between machines can avoid the problem of thermal separation found in the combination of thermoplastic and elastomeric materials, because the temperature of the cavities can be controlled entirely separate from one another [6].

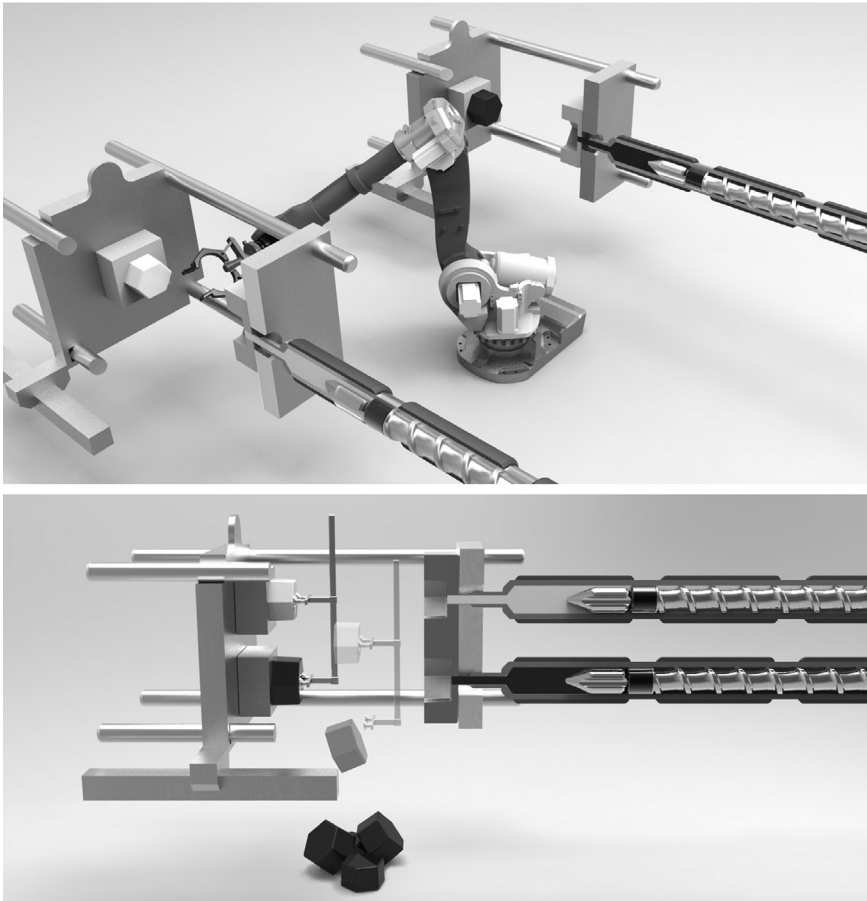


Figure 1.20 Relocating technique (bottom) and insert technique (top).

In general, flexibility in the repositioning process enables the greatest degree of design freedom of all the tool technologies discussed in this chapter [2,42]. This, however, has to do with the selection of the injection position; but there are limitations when it comes to creating delicate geometries, because handling can be difficult [46]. For this reason, primarily simpler and more robust contours are made [2,27].

Generally, positioning the components is connected to challenges during the handling process [46]. Short-term shrinkage must be reckoned with during the repositioning [2,7,27]. In particular, placing the component on cores is regarded as highly critical [7]. Semicrystalline materials do display a greater degree of shrinkage and are at higher risk for this problem. Amorphous thermoplasts are at greater risk of breaking during

this process due to their brittle nature [7]. Besides problems during the actual insertion process, quality defects, such as warpage, can also occur later (see Section 1.4.3.1) [2,6].

Regarding the cycle time, simultaneous injection is possible¹ [46], yet repositioning with a handling machine usually requires more time than a technique such as repositioning using a rotating tool concept. The repositioning method is often used for larger quantities, while the insertion technique is usually reserved for smaller series and prototypes [6]. In addition to economic aspects, there are technical necessities that make the utilization of transfer methods imperative. For instance, this is the case for very large components and accordingly large tools, which cannot be moved on a rotary disk due to their mass (see Section 1.5.4.3) [6,7,27]. Even when components cannot be held on an index plate (see Section 1.5.4.4), the repositioning method is used [7]. The insertion technique is especially suitable for thermoplast-elastomer composites [2,42]. In cases where there are large geometry changes between the first and second component concerning the required tool size and clamp force this technology is favorable [30].

The longer repositioning times of the transfer methods negatively influence the interface temperature (see Section 1.3.2), and, thus, the adhesion as well. The larger temperature differences in combination with hardly reproducible cooling conditions can lead to increased interface stresses (see Section 1.4.3). One advantage of this technique is the ability to positively influence the cooling times and other processing parameters independently. This option is partially available for the repositioning method, and fully for the insertion method.

1.5.4.3 Rotary Disk

In tools with rotary disks, one side of the tool is rotated to move the formed component to the next station. The rotary plate is almost always located on the side of ejection, because if it were positioned near the nozzle, a rotating sprue would be needed as well [6]. Depending on the number of components, the angle of rotation varies. Thus, for two components, the angle is 180°; for three, it is 120°, etc. In order to reduce the cycle time, one station of the rotary disk can be reserved for the demolding process in the closed tool. For this purpose, an opening is needed in the nozzle part of the tool [48]. Rotary disks can be a fixed

¹In contrast to the previous section, *simultaneous* refers to the simultaneous action of several injection units at different tool positions, not the simultaneous filling of cavities.

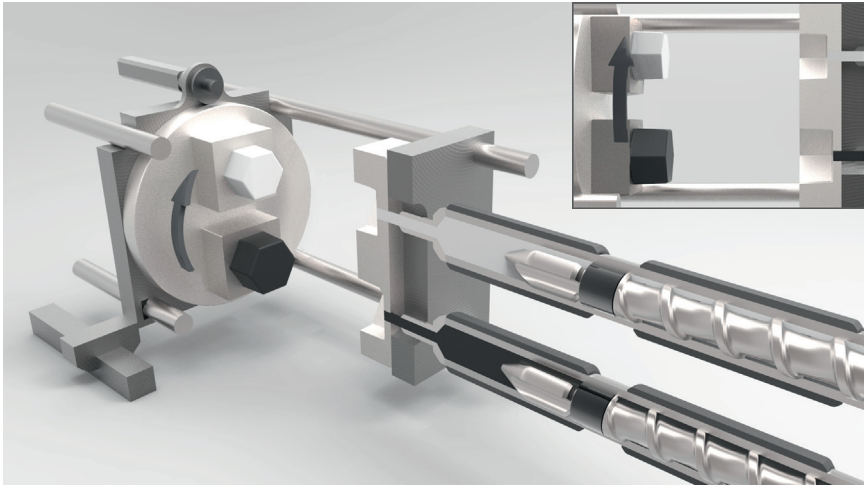


Figure 1.21 Rotary disk.

part of the injection molding machine, but they also can be integrated into the tool [6]. The machine-integrated version is more common in larger machines, the tool-integrated version in smaller machines [42]. The power unit of the rotary disk is achieved either hydraulically or with servo motors [46] (Figure 1.21).

If the rotary disk is an integral part of the machine, the tool itself will have a simpler construction [7]. Moreover, the rotary disk can be used for various tools [7,48]. Because the molded parts are securely anchored in the rotating cavity, precision when positioning is not a challenge compared to transfer or index tools [6].

One disadvantage of the rotary disk technology is its need for a large amount of space. Due to a higher mold height, tie bar extensions of 200 mm and more are needed [46]. The tool width is also larger and requires more space between the tie bars [49]. Values ranging between approximately 50–100 mm are common [46]. The ejection plates turn with the tool and therefore must be present at every station [48]. With regard to the component geometry, there are limitations because an enlargement of the cavity volume in the second cycle or later cycles can be done only via the mold contour on the nozzle side [6,27].

Most times, the projected area by the part geometry differs at the various stations of the rotary disk. The consequence is an asymmetrical distribution of the inflation [4,6]. In the case of larger differences, a design that includes 70%–80% of the maximum clamping force must be selected [47]. Moreover, the cycle and the limited thermal separation prevent an independent optimization of the single processes, meaning

that compromises must be made with regard to the cooling and holding pressure times [4,6].

Challenges arise when dealing with larger molded parts. Due to the occurring tilting torque, the ability to utilize rotary tables on machines with a clamp force of up to 2000 tons is limited [49]. Also, the rotational movement itself poses quite the challenge in itself. The rotary feedthrough of supply lines, as well as the fact that size is limited due to stability issues [49], limit the dimensions of the hydraulic and cooling supply [46]. In addition, there are limitations concerning the thermal separation at the rotational feedthrough segment [49].

Thanks to their high rotation speeds and simultaneous injection at the stations, rotary disk tools enable short cycle times to be achieved [26]. When this advantage is combined with a design freedom that is larger by far than for the slider technology [6,27] the rotary disk becomes one of the most commonly used multicomponent tool technologies [30].

The achievable interface temperatures depend upon the theoretically required cooling times of the components injected at the individual stations. Should these diverge strongly from one another, then some components will cool down excessively, and the interface temperature (see Section 1.4.2) during the following injection step will be lower. In addition, an increase in the interface stress should be expected (see Section 1.4.3). When cooling times are similar to one another, the fast and reproducible rotational movements are beneficial.

1.5.4.4 Index Plate

The index plate concept is similar to that of the rotary disk. However, here, the entire ejection side of the tool is not rotated, but simply a plate, or a beam or cross. As was also the case for the rotary disk, the number of stations is not set. In addition, this concept enables stations to be used merely for cooling or demolding [46]. During a rotation process, the machine ejector and the attached index plate are extended [30], and then subsequently turned by one station and drawn in again. The rotating cores can be pulled behind the cavity, turned, and, subsequently, reinserted into the cavity from behind [6]. The rotational part of the movement is powered by a servo, or hydraulic motor [46]. Also, rotation axes are also possible outside the tool [6] (Figure 1.22).

Two designs are distinguished here: index plate tools, which have a completely rotating tool plate; and hub tools, in which only a beam or cross completes the rotational movement. The latter is sometimes also referred to as an index plate [4]. The components are kept on collapsible

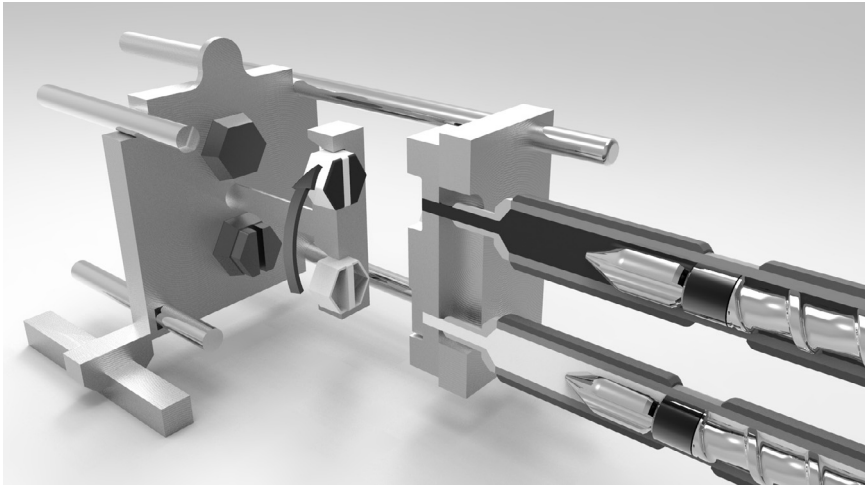


Figure 1.22 Index plate technology.

cores with undercuts [46,48]. Due to the low total mass, higher speeds can be achieved with lifting than with the rotating tool [46]. As the ejector plate remains unmoved, only one ejector system is required [48].

The problem of material insertion is also not prevalent here. In addition, geometries can be created to which a component will be added, either on the side of ejection [48] or on both the side of the nozzle and the side of ejection [7,27,30]. Depending upon the application, in particular when using rotating tools, hot runner systems are applicable in only a limited sense [46,48].

Utilizing index plate tools is suitable when only one product or a few products are to be manufactured on a machine. Thus, a machine-integrated rotary disk would not amortize itself. Moreover, index plate tools are often utilized due to their large degree of component design freedom [7]. With regard to the attainable composite adhesion, comparable criteria apply as for the rotary disk tool.

1.5.4.5 Linear Systems

The simplest, linear system is the sliding table, which is a cavity plate located on the ejection side that moves between two or several positions vertically. At each position, there is an injection unit for the according component. Injection is sequential, meaning that only one injection unit is active at a time. Similar to the rotary disk tool, the standard method only allows a nozzle-sided cavity variation. However, in

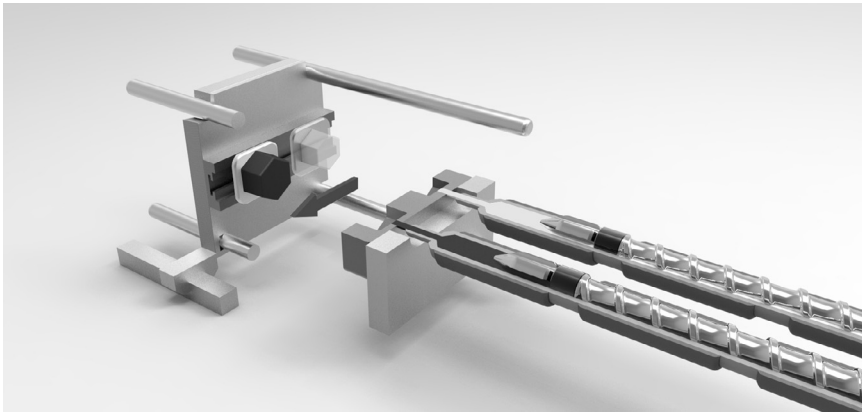


Figure 1.23 Sliding table.

the style of hub systems, there is a variation in which a central element loaded with cores is used, and which enables an adjustment of the cavity on the side of ejection. Thanks to its simple technology, a sliding table involves relatively low investment costs. The longer cycle times that result from the sequential processing are the reason that this tool concept is mostly employed for smaller quantities in smaller series [42]. The sliding table concept is depicted in [Figure 1.23](#).

The Paternoster technology represents a concept that is eligible to compete with regard to the cycle time. Analogous to the elevator concept with the same name, the cavities on the same side of the tool are shifted sideways and continue downward in a linear motion until they finally rise again in the opposite direction. By means of employing several cavities, a simultaneous process cycle, as well as a demolding, are enabled in the closed tool. The movements of the cavities are screw-driven. The main benefit in comparison to rotary disk tools is the need for less space, meaning holm adjustments are not needed [46]. With regard to the composite adhesion, for both tool concepts, similar effects can be expected as those for rotary disk tools.

1.5.4.6 Horizontal Turning Technologies (Stack Turning Technologies)

While the previously described rotating technologies were based on a rotation on a horizontal axis, the technologies described in the next sections consist of tool rotations that take place on vertical axes. The concept utilizes a central plate that completes the turning movements.

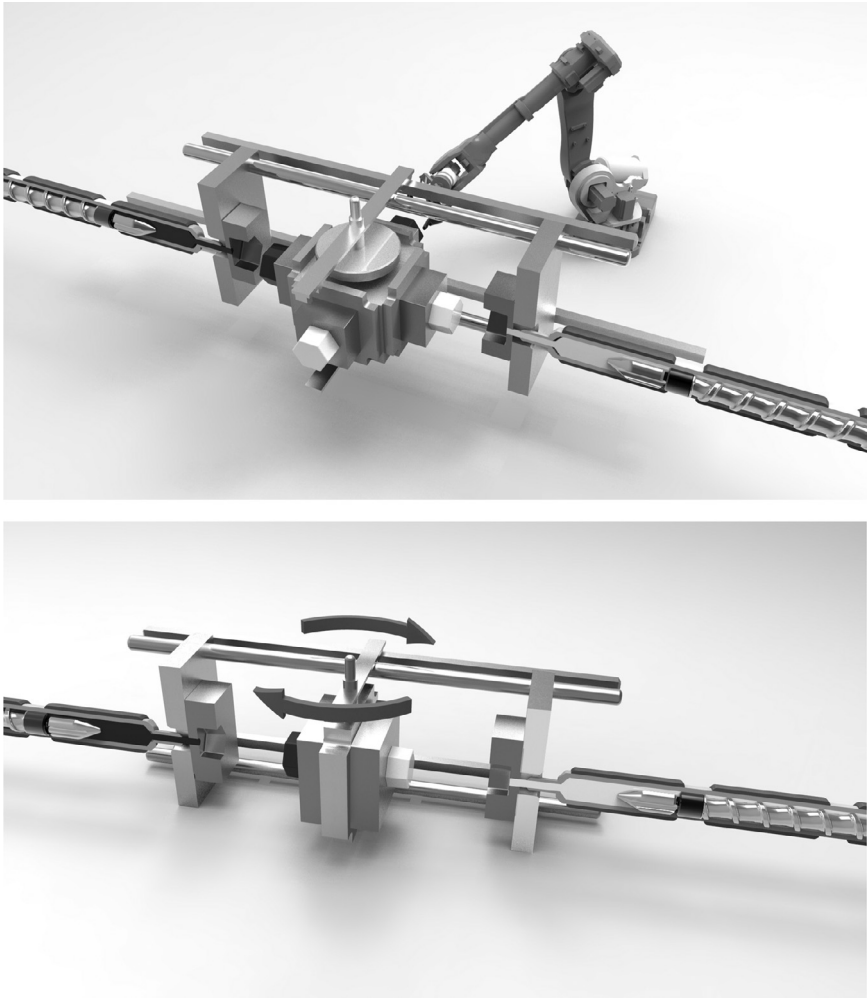


Figure 1.24 Cube technology (top) and stack turning plate (bottom) by comparison.

Depending upon the number of planned stations, there will either be a plate (two stations), or a cube (four stations). The variation with two stations is referred to as stack turning technology [4], while the variation with four stations is commonly called a rotary central block [27] or cube technology. These concepts are shown in Figure 1.24.

Perhaps the greatest advantage of this technology in comparison to others is that the clamping force provided by the machine can be utilized for both parting planes owing to their being arranged in opposite directions. Therefore, when employing two injection processes with identical clamping force requirements, the needed clamping force can

be divided in half; thus, the machine size can be reduced [2,4,46,48]. The required amount of clamping surface reduces because, in contrast to rotary disk tools, the cavities of all stations do not all have to be positioned on one parting plane, but can be distributed over a second parting plane, which is located across too [4]. In cube tools, the additionally available stations on the sides can be used for intermediate steps, such as coating, cooling, demolding, or inserting of additional components [2,46,48]. The separate parting planes also enable injection compression processes, which are often employed for optical components [42,49]. Limitations arise, however, concerning the positioning of the injection units because the second injection unit must always face in the opposite direction of the first in the movable tool plate [48]. Although complex redirections of the melt can be avoided [49], a need for a larger space for the machine results.

Because the supply lines can be directly hooked up and lack a rotary feedthrough, faster processes with higher levels of required cooling can be realized using stack mold technologies [49]. From an economic perspective, cube technologies only prove useful when at least three stations of the cube are utilized, because their tool costs are comparably high [49]. The realizable geometries are comparable to those of the rotary disk tool, because a variation of the cavity is also only possible via one side of the tool (i.e., of the cube). Due to the advantage of the reduced clamping force and surface, the cube technology is predestined for flat and large components, or applications that require a high number of cavities [42,46].

Since at least one pause in the cycle between injecting the first and second components takes place in the four-station version, lower interface temperatures result (see Section 1.4.2), and, due to the thermal properties of the materials, mostly higher interfacial stresses occur (see Section 1.4.3). These have according effects on the composite adhesion. However, this intermediate step can be used to apply adhesion enhancing methods, such as plasma treatments. This, in turn, positively affects the composite adhesion by inducing increased interface compatibility (see Section 1.4.1).

In addition to the standard technology, further variations of the stack turning technology exist. Core segment rotation technology utilizes a center plate that is vertically divided into different segments, which each rotate on their own axes (Figure 1.25). One advantage is that smaller masses have to be moved when turning, and, owing to the smaller rotation radii, lower opening strokes are needed. Stations with either two stations or four stations are used [50].

In the case of applications where the assembly of the created components is to be carried out, there is the option of what is called double

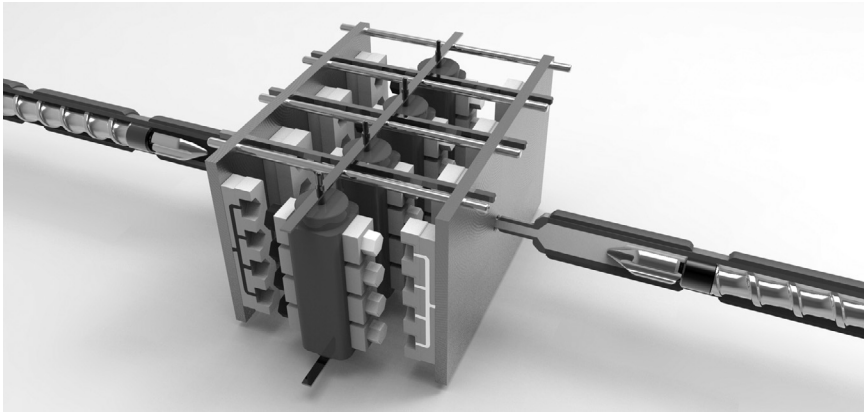


Figure 1.25 Core segment rotation technique.

cube technology. Here, instead of merely one cube, there are two consecutive cubes situated between the tool plates. A molded part is created in each cube. The intermediate positions on the sides can be used to insert additional components. The final assembly step is carried out in the parting plane between the cubes. A large advantage of this method is that, in addition to process integration, that components from the same cavity pairs are always combined with one another owing to the higher number of cavities in the tools. With the correct settings, the reject rate can be considerably reduced [46,51].

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