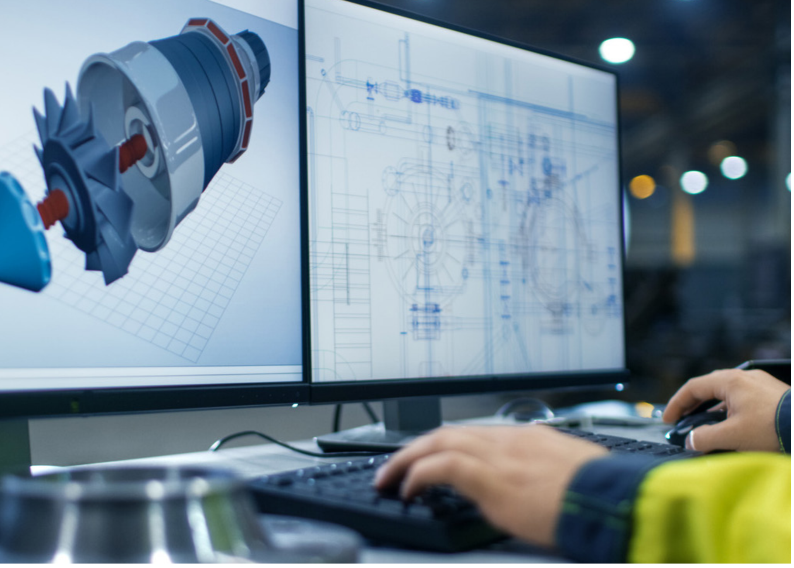

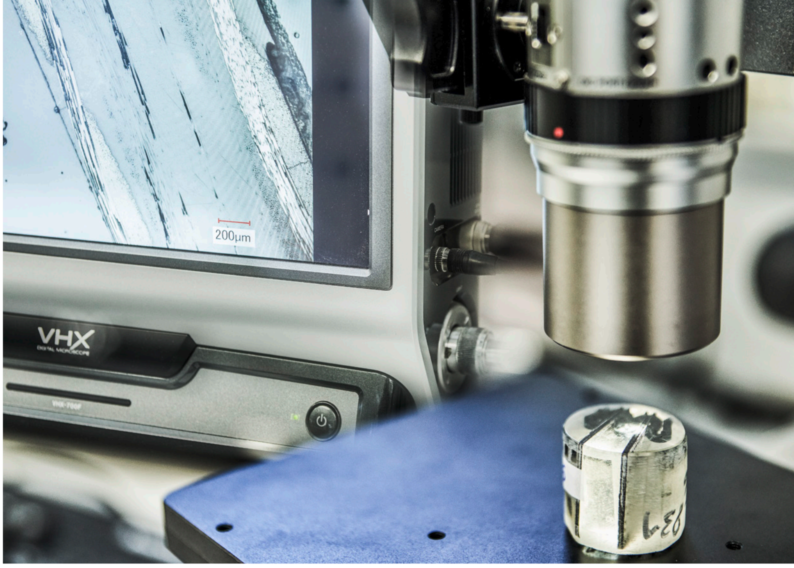

Tepex®

PROCESSING GUIDELINES

Envalior

Imagine the Future

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1. ABOUT TEPEX®

This brochure will give you an overview of the structure of Tepex® as well as its properties and possible applications. You will also learn more about our CAE services, which allow us to lend you our support throughout all stages of the development and manufacture of components made from Tepex®. Our Tepex® high–performance thermoplastic com–po–site has made a name for itself as a lightweight material suitable for large–scale production and for use in all kinds of applications. Its thermoplastic matrix and its consistently high quality make it an ideal material for fully automated and reproducible manufacturing and processing operations. Tepex® is used in automotive engineering, the sports industry, consumer electronics and a diverse array of other sectors.

Tepex® is a group of fully impregnated and consolidated composite sheets comprising high–strength continuous fibers (or long fibers in the case of Tepex® flowcore) and a thermoplastic matrix. These organo sheets, as they are also known, can be processed in short cycle times to make complex components through the application of heat and subsequent forming. For the most part, glass and/or carbon fibers are used for the continuous fibers in the form of woven fabrics or other semi–finished textile products. Matrix materials include thermoplastics such as polypropylene, polyamide, polycarbonate, thermoplastic polyurethane or bio–based thermoplastics. The key attributes of Tepex® can be summed up as follows:

The key attributes of Tepex® can be summed up as follows:

– High stiffness

– High strength

– Low density, offering excellent potential for use in lightweight applications

– Short cycle times in component production

– Thermoplastic matrix, enabling overmolding and welding

– High design flexibility

– No solvents

– Recyclable

– High capacity for energy absorption

– Low coefficient of thermal expansion

– Good dimensional stability and chemical and corrosion resistance

1.1. Matrix systems

We use only thermoplastics as matrix materials for Tepex®. Their properties are very favorable for processing in particular. Thermoplastic matrices enable very short cycle times and eas–ily recyclable components, and they do not present any critical occupational hygiene issues. Furthermore, fiber–reinforced thermoplastic composites can be combined with other thermo–plastics with identical or compatible matrices and undergo the same processing methods. That opens up much greater freedom in component design. The matrix material not only acts as an "adhesive" for the reinforcing fibers, but also performs numerous essential functions in the composite.

Those include:

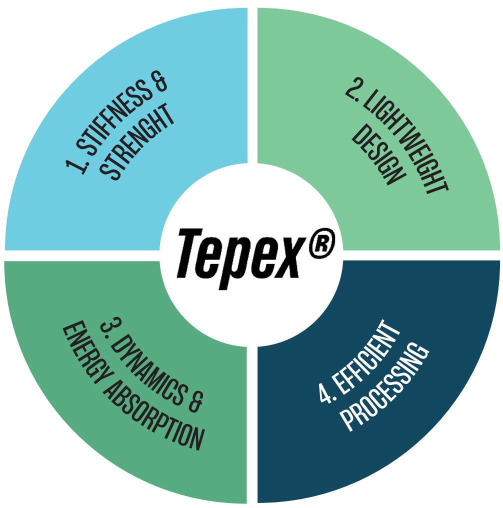
– Transducing forces into the fibers

– Transferring forces from fiber to fiber

– Protecting fibers from the environment

– Fixing the fibers in the desired geometric layout

– Absorbing mechanical loads, particularly those perpendicular to the fiber direction, as well as shear loads



The Tepex® range encompasses thermoplastics including the following:

– Various polyamides (such as PA 6, PA 6.6, PA 4.6)

– Polypropylene (PP)

– Thermoplastic poly–urethane (TPU)

– Polycarbonate (PC)

– Bio–based thermoplastics (such as PLA, PA 4.10, PA 10.10)

– High–temperature thermoplastics (such as PPS, PEI)

1.2. Reinforcing fibers

As with other fiber–reinforced composites, Tepex® fibers are tasked with absorbing the loads exerted on the component in question. That means they need to provide high rigidity and strength as well as the lowest possible density. Experience shows that most materials exhibit significantly better mechanical properties as fibers than in compact forms. Glass and carbon fibers now enjoy widespread use as structural materials due to their low void density in fiber form.

1.2.1. Glass fibers

Glass fiber is an inorganic fiber type that exhibits high strength derived from the strong covalent bond between silicon and oxygen (SiO_2 = quartz). Glass fibers are manufactured from molten material that is cooled rapidly to prevent crystallization and allow the formation of a three–dimensional network with an amorphous structure.

Consequently, the glass fibers have isotropic properties.

The properties of glass fibers – a summary:

– Highly cost effective with excellent mechanical characteristics
– Very high tensile and compressive strength
– Exceptional thermal and electrical insulation capacity
– Completely non–flammable
– Fibers do not absorb moisture
– Resistant to decay

There are various types of fiber with different chemical compositions, of which the type known as E–glass is by far the most commonly used. It is also the one most often used for Tepex®. The diameters of glass fibers range from 9 µm to 24 µm. The thickness of a roving of glass fibers (roving = a bundle of parallel continuous fibers) is referred to as the yarn count and can be measured in a number of different units, but we use tex (1 tex = 1 gram per 1,000 meters).

This is a way of measuring the diameter and quantity of individual filaments in a glass fiber yarn or roving. We generally refer to fine types with a yarn count of less than 300 tex as filament yarns and those with a yarn count greater than 300 tex as roving yarns. Refer to the relevant Tepex® data sheets for the yarn counts of the various fibers.

1.2.2. Carbon fibers

Carbon fibers are technical fibers that can be manufactured from a precursor (usually polyacrylonitrile (PAN) fibers) in a temperature range of 1,300°C to 3,000°C and that have a carbon content of between 92% and 99.9% by weight. Carbon fibers are constructed in layers (a graphite structure), with their high strength and modulus of elasticity based on the strong covalent bonds between the carbon atoms within those layers. Between the individual layers themselves, however, the bonds are only weak, which means that the properties of the material perpendicular to the fiber direction are relatively limited. Due to the extreme nature of its properties, carbon fiber is the real standout among the many different kinds of reinforcing fibers.

The properties of carbon fibers – a summary:

– Very low density
– Extremely high strength and modulus of elasticity
– Virtually linear elastic behavior
– Pronounced anisotropy
– Very low coefficient of thermal expansion
– Resistant to most acids and alkalis; biocompatible (not harmful to the human body)
– Good electrical conductivity (electrical shielding)

Like their glass counterparts, carbon fibers are divided into numerous different types, some of which vary considerably in terms of their mechanical properties. The most appealing from a cost–effectiveness standpoint – and the type most often used for Tepex® – is the HT (high tenacity) variety, which offers excellent strength and good rigidity. Carbon fibers have diameters ranging from 5 µm to 10 µm. As with glass fibers, carbon fibers are conventionally supplied wound onto a reel in the form of a continuous roving or "tow." These tows consist of multiple individual filaments. The number of filaments in a tow is indicated with a K number (1K = 1,000 filaments per tow). Carbon fiber with a K number greater than 24 is referred to as "heavy tow."

1.2.3. Other types of fiber

Glass and carbon are not the only fibers available. There are numerous other fiber materials suitable for use in Tepex®, but they tend to be needed only for very specific sets of requirements:

Aramid fibers are extremely tough and exceptionally well suited to applications in which energy absorption is a priority. For example, aramid is suitable for applications that require puncture or impact resistance, as well as for protective equipment. However, the fact that aramid fibers are so much tougher than carbon fibers, for instance, does mean that they are less rigid.

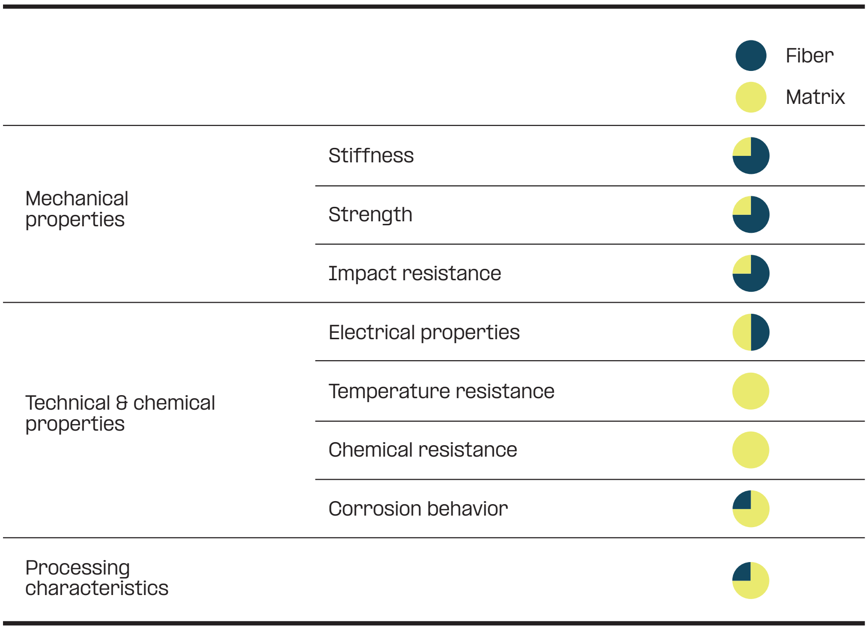
Natural fibers, such as flax and mineral fibers like basalt, are other examples of variants that can be used as Tepex® reinforcing fibers. They are sustainable alternatives that can be made using less energy or from renewable raw materials, thereby helping to protect the environment and the climate. Despite relatively weak mechanical properties, natural fibers can offer advantages in terms of acoustic insulation or vibration damping, for example, opening up an array of specific potential applications for such fibers from a technical perspective.

The Tepex® manufacturing process makes it easy to combine different types of fiber in one composite structure. As a result, it is possible to mix a range of fiber types together in a way that makes the most of their advantages while compensating for the disadvantages of each type.

1.3. Fiber–matrix adhesion and division of tasks between fiber and matrix

The properties of a composite will be optimized only if the forces exerted on the material can be directed into the fibers and transferred from fiber to fiber. This requires good adhesion between fiber and matrix. Deliberately selecting sizing (an agent used to promote adhesion) that is adjusted for each material and applied to the fibers after they have been manufactured, as well as any necessary additives for the thermoplastic along with an adhesive agent, ensures that Tepex® always has the best possible bond between the fibers and the matrix material.

Figure 1: How functions are split between fibers and the matrix



It is worth noting that the processing properties are determined almost exclusively by the matrix material.

We will explore this aspect in more detail in the course of this brochure.

1.4. Semi–finished textile products

Special semi–finished textile products are used to manu–facture fiber composites in order to optimize their design in terms of the required fiber orientation and with a view to ef–ficient and reproducible component production. For the most part, four different types of semi–finished textile products are used for Tepex®.
Those are:

– Textiles with 0°/90° fiber orientation: bidirectional woven fabrics

– Textiles with (quasi–)unidirectional fiber orientation: unbal–anced/unidirectional woven fabrics

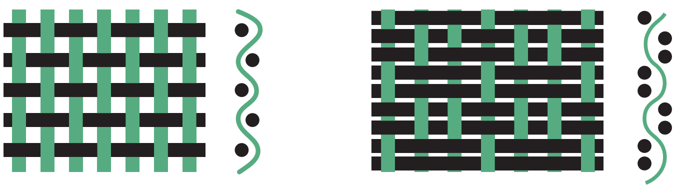
– Textiles with others than 0°/90° fiber orientation for multi–axial complexes

– Textiles with quasi–isotropic properties: randomly oriented mats (non–wovens) or cut fibers

– Unidirectional spread fibers

Woven fabrics consist of warp and weft interlaced at right angles, resulting in a bidirectional reinforcing effect at angles of 0° and 90°. There are various types of weave used for woven fabrics, but those most commonly used for Tepex® are plain weave and twill weave (Figure 2). Twill weave is a good compromise between achievable mechanical properties, formability and ease of handling, which is why it has become the type of weave most commonly used in fiber composite technology. However, plain weave is also used in many appli–cations because it is so easy to handle.

Figure 2: Plain weave (left) and twill weave (right): simplified illustrations



When a woven fabric has a high proportion of either warp or weft relative to the other, it is referred to as a (quasi–)unidirectional woven fabric, with a reinforcing effect that acts primarily in either the 0° or 90° direction as applicable.

Multiaxial woven fabrics consist almost exclusively of non–crimped fibers running parallel to each other. With this kind of semi–finished textile product, it is possible to set almost any reinforcement direction, within certain limits.

Unidirectional spread fibers are the basis for the ther–moplastic tapes in the UDea® family. These fully im–pregnated fiber tapes can themselves undergo further processing to make semi–finished products with textile properties such as biaxial tape fabrics or multiaxial non–crimped fabrics (NCFs).

The Tepex® coding system reflects the various textile types:

– C: carbon woven fabric

– RG: roving glass woven fabric

– FG: filament glass woven fabric

– CUD: carbon woven fabric, (quasi–)unidirectional

– RGUD: roving glass woven fabric, (quasi–)unidirectional

– RGUDm: roving glass woven fabric, unidirectional, suitable for multiaxial structures

– CNW: carbon non–woven

– A: aramid woven fabric

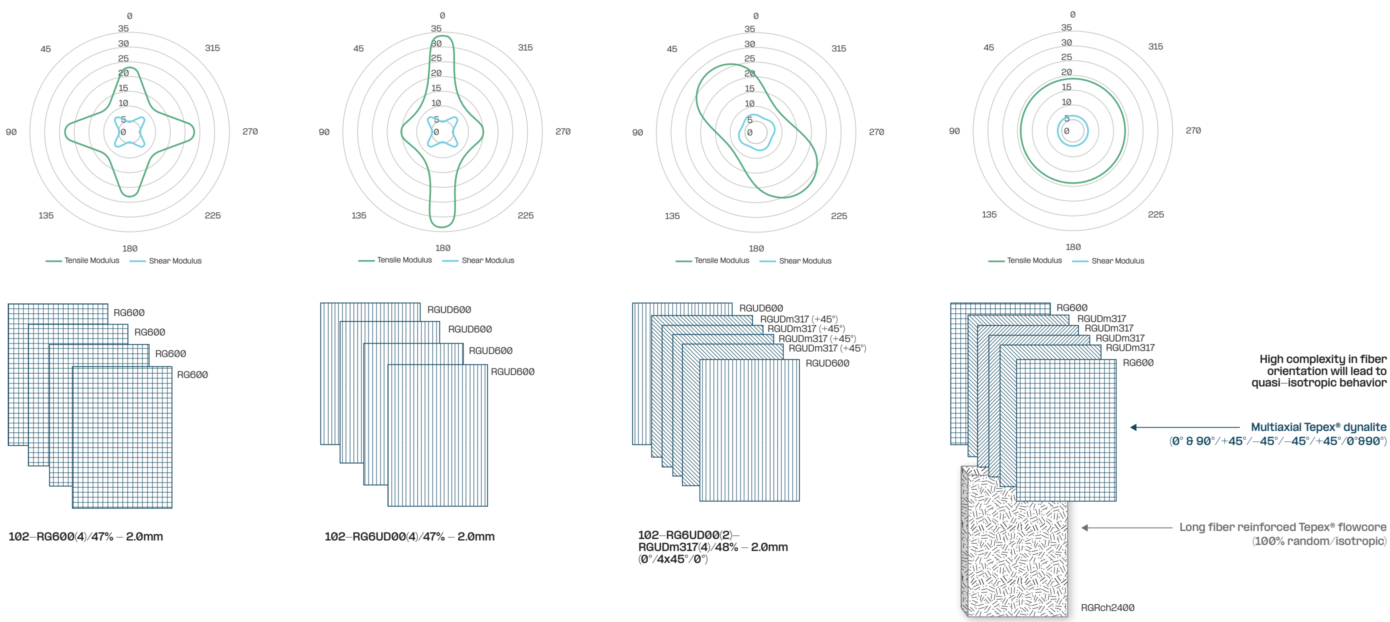
– F: flax woven fabric

1.5. Tepex® laminates structures

In very rare cases, fiber composite structures bear all their load on one axis, meaning that just one fiber direction would be adequate. The often multiaxial stresses on the material therefore usually require multiple fiber orientations, giving rise to various laminated structures (multi–layer composites).

In principle, any of the semi–finished textile products mentioned above can be combined for Tepex®. This gives designers an opportunity to engineer the laminate in the most appropriate way for the load it will need to bear. In addition to conventional woven–fiber–reinforced laminates, multiaxial structures can therefore also be implemented, extending as far as quasi–isotropic properties as shown in the examples in Figure 3. In the case of multiaxial loads, a conventional bidirectional woven fabric is often the best solution, without any need for anything more complex. The external forces are distributed across the main directions of the fibers and the composite achieves much higher strength and rigidity than would be the case with a quasi–isotropic, multidirectional structure, the properties of which are often scarcely any different from those of a randomly oriented fiber mat.

Figure 3: Examples of laminated structures with Tepex® (strength of a glass–fiber–reinforced PA6 as a function of angle, shown as a polar diagram including the respective laminate structures)



1.6. Tepex®–family

1.6.1. Tepex® dynalite

The Tepex® dynalite materials comprise one or more layers of semi–finished textile products with continuous fibers embedded in a matrix of technical thermoplastics. This type is fully impregnated and consolidated, meaning that all the fibers are sheathed in plastic and there are no air pockets in the material. Tepex® dynalite therefore delivers maximum strength and rigidity while maintaining a low density.

1.6.2. Tepex® flowcore

The fibers contained in Tepex® flowcore have a finite length, which makes this material type a good fit for compression molding and opens up greater freedom for design. The fibers are fully impregnated and consolidated in this case as well. The flowcore family also includes structures consisting of a combination of continuous fibers (Tepex® dynalite) and long fibers (Tepex® flowcore). For example, the continuous fibers are located on the outside of the laminate, while the long fibers run through the middle. This results in a fiber–reinforced composite with maximized bending strength, and because of the flowability of the core – hence the name "flowcore" – it allows for the molding of complex components.

1.6.4. Tepex® anti–ballistic

Tepex® anti–ballistic materials, made from woven aramid fabrics, are designed specifically for optimally absorbing and dissipating energy with the aim of protecting people and hardware. As with the other Tepex® families, Tepex® anti–ballistic has an advantageous strength–to–weight ratio, which has beneficial effects in vehicle manufacturing and, in particular, in making ballistic body armor more comfortable to wear.

1.6.5. Tepex® UDea®

Materials in the UDea® family are fully impregnated thermoplastic tapes. The reinforcing fibers are entirely aligned with the production direction of the tapes, allowing for the transfer of energy to be directed in the ideal orientation. UDea® tapes boast very high strength in the fiber direction and are particularly well suited to winding processes and to the local reinforcement, or patching, of components.

1.7. Nomenclature

The following information is used to provide clear and unambiguous descriptions of fiber–reinforced composites:

– Fiber type (glass, carbon, etc.)

– Type and grammage of the semi–finished textile product (woven fabric, non–crimped fabric, etc.)

– Plastic (PP, PA6, etc.)

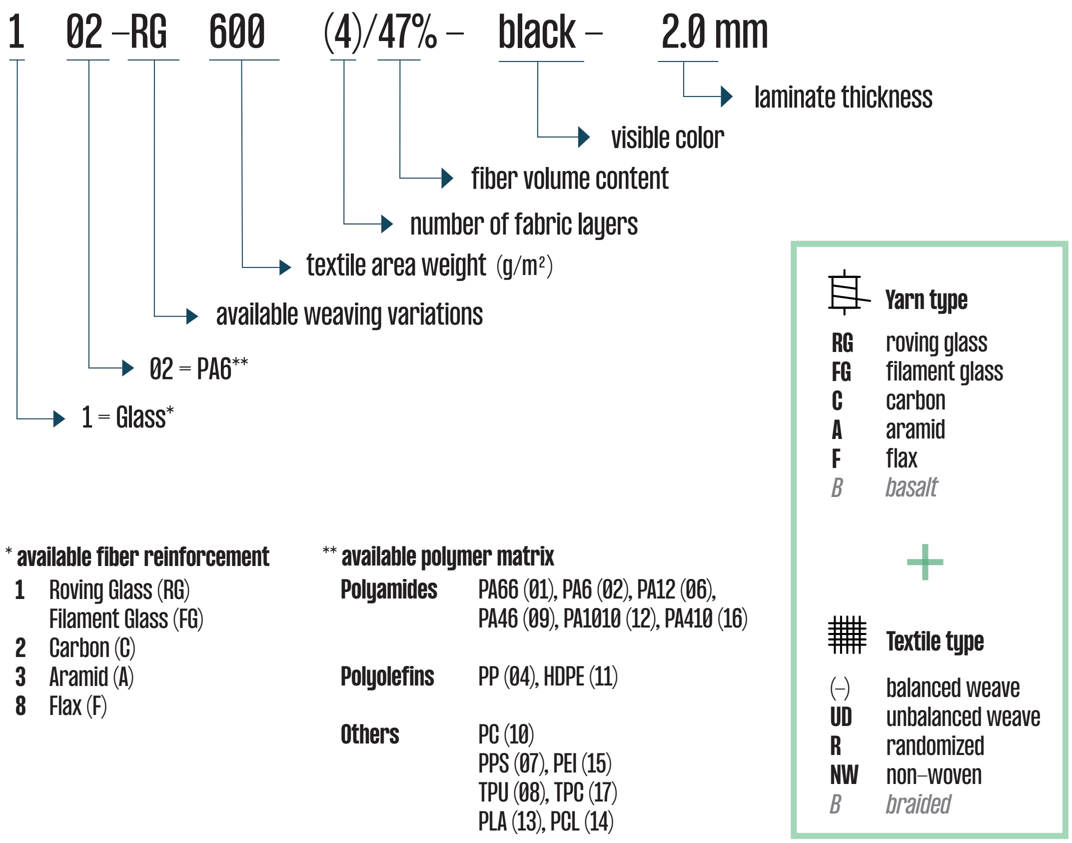
– Number of layers in the laminate

– Fiber content

– Direction in which fibers are arranged

Because Tepex® dynalite is fully impregnated and consolidated, it can be used as a basis for calculating all other values such as laminate thickness and fiber content by weight. The Tepex® material code contains all the relevant information.

Figure 4: Breakdown of a Tepex® material code



1.8. Tepex®–properties

Fiber–reinforced composites are notable for their high strength and rigidity coupled with very low density. These are the ideal characteristics for a lightweight material. The table below shows the key characteristics of a few typical Tepex® types.

Figure 5: Key characteristics of selected Tepex® materials

Tepex® Material type	Fiber	Polymer	Fiber Volume Content (Standard)	Density [g/cm³]	Siffness (ISO 527)	Strength (ISO 527)	Energy absorption (ISO 6603)	Glass transition temperature (amorph) Crystallit melting point (semi–crystalline)
Tepex® dynalite								
101	Glass	PA6.6	47 %	1,81	++	++	++	260 °C
102	Glass	PA6	47 %	1,81	++	++	+++	220 °C
104	Glass	PP	47 %	1,68	+	++	+++	165 °C
108	Glass	TPU	45 %	1,84	++	++	++	190 °C
110	Glass	PC	47 %	1,84	++	++	+++	145 °C
201	Carbon	PA6.6	45 %	1,42	+++	+++	o	260 °C
202	Carbon	PA6	45 %	1,42	+++	+++	o	220 °C
208	Carbon	TPU	45 %	1,46	+++	+++	+	190 °C
813	Flax	PLA	41 %	1,33	+	o	++	170 °C
Tepex® flowcore								
102	Glass	PA6	47 %	1,81	+	+	++	220 °C
104	Glass	PP	47 %	1,68	+	+	++	165 °C
UDea® Tapes								
K20HG60	Glass	PA6	40 %	1,70	+++	+++	++	220 °C
Q20HC60	Carbon	PA410	50 %	1,45	++++	++++	++	250 °C
++++ high performance (> 100 GPa / > 150 MPa/ n.a.)								
+++ outstanding (> 40 GPa / > 600 MPa / > 40 J)								
++ very good (> 20 GPa / > 300 MPa / > 30 J)								
+ good (> 10 GPa / > 150 MPa / > 20 J)								
o low (< 10 GPa / < 150 MPa / < 20 J)								

1.8.1. Flame–retardant properties with Tepex®

The high fiber content and the use of non–flammable materials, such as glass, mean that most Tepex® types inherently possess excellent flame–retardant properties. Particularly in cases in which flames hit one surface of a Tepex® panel, there is a significant effect that occurs almost irrespective of the matrix material used, which is that the polymer on the surface facing the flame melts at first but, because of the excellent fiber–matrix adhesion, the complete impregnation of the fibers and the high fiber content, it cannot drip burning material. Instead, the plastic breaks down. The resultant decomposition products, which are usually non–flammable, remain stuck to the fibers and form a heat shield. This will continue until there is no more flammable polymer for the flame to reach. That means that Tepex® can withstand open flames reaching temperatures in excess of 1,000°C for several minutes.

However, if the flame reaches an open edge, the reinforcing fibers may act like a wick. The flame will very slowly make its way along the fibers, but will not extinguish itself. In relevant applications, it is therefore always advisable to seal the open edges, such as by overmolding the Tepex® insert or using suitable mounting elements. If that is not possible and thus it is necessary for flames to self–extinguish at an open edge, certain Tepex® types can be equipped with a suitable halogen–free flame retardant.

2. PRODUCTION METHODS FOR *COMPONENTS MADE FROM TEPEX®*

The process of manufacturing components made from Tepex® includes the following steps:

1. Heating the composite sheet blank above the melting point of the thermoplastic. To be more precise: temperature range above the crystallite melting point in the case of semi crystalline plastics or above the glass transition temperature in the case of amorphous plastics. The processing temperature range must nevertheless be significantly below the respective degradation temperatures.
2. Transporting the heated blank to the mold
3. Mounting and positioning the heated blank in the mold
4. Forming using suitable tooling technology
5. If applicable, injecting or pressing on an additional thermoplastic component (combined technologies)
6. Cooling and removing from the mold

Because of this workflow, the forming of Tepex® is also referred to as thermoforming. However, there are a few things to bear in mind:

– Organo sheets are not formed in the elastic temperature range as with conventional thermoforming, but above the melting point.

– The Tepex® semi–finished product is subject to equal pressure on all sides during forming and cooling thanks to the use of suitable tooling technology and process management.

– Owing to the high–strength and high–rigidity continuous fibers, even in the temperature range used for forming the polymer matrix, no changes in cross–section or elongation occur as in conventional deep drawing; instead, only rearrangement of the fibers (draping) takes place.

We will provide a brief introduction to the heating process and the various forming methods and technologies below. For further information about forming mechanisms for organic sheets and the resultant mold design, refer to Section 3.

2.1. Heating

Heating Tepex® reduces the viscosity of the thermoplastic sufficiently to grant the individual fibers adequate freedom to move during the forming process. This is the only way to ensure that the draping mechanisms explored in Section 3 can be put into practice and to prevent the formation of wrinkles and cracks in the material.

The process calls for adherence to the following requirements:

– Tepex® needs to be formed above the melting point of the thermoplastic material used.

– The heating temperature must be high enough for the fibers to maintain sufficient freedom of movement even after being transported to the mold, at the moment when the mold is closed (in other words, transport time/distance must be kept as short as possible).

– The heating temperature and time should be set such that any oxidative degradation is averted.

– The heating process should be designed to ensure that temperature is distributed as evenly as possible across the entire Tepex® surface.

– Temperatures should be regulated in such a way as to prevent temperature increases and spikes.

– In the interest of efficient process management, heating should not become a determining factor in cycle time.

The following methods are available in principle:

– Heating by radiation (infrared)

– Heating by convection (air flow)

– Heating by induction (not possible for every design)

– Contact heating (not recommended for automated processes in series production)

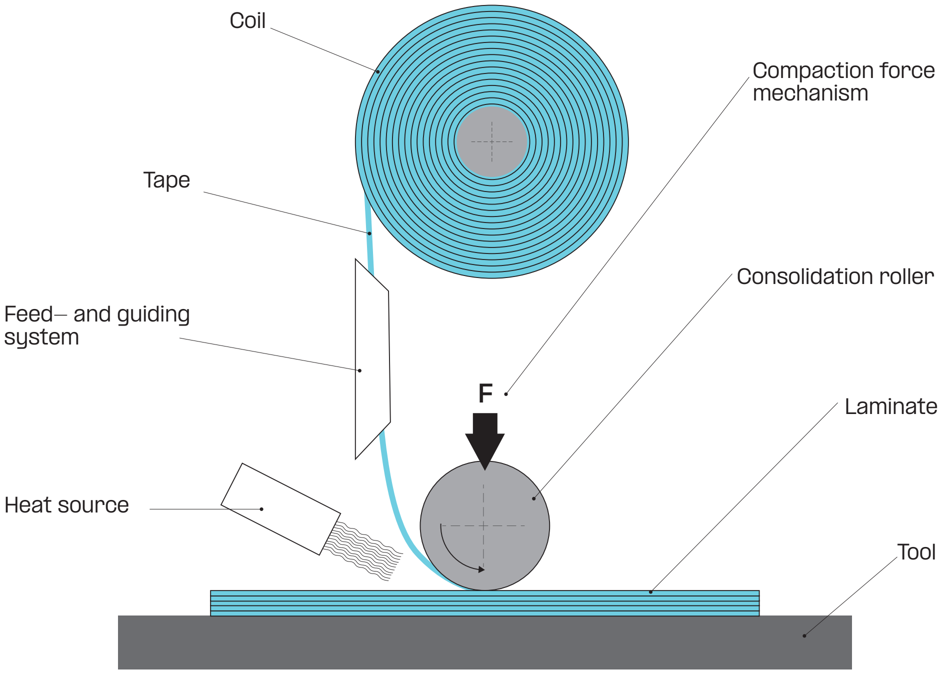
Infrared radiation refers to electromagnetic waves in the spectral range between visible light and microwave radiation. The semi–finished product blanks absorb the infrared radiation and heat up as a result. The inside of the composite is heated as well due to thermal conduction. Because thermoplastics and fibers have high absorption capacity in the infrared range, this transfer of heat is very effective.

Another heating method in widespread use in the plastics industry is convection, or the use of circulated air. Convection ovens with material added using the paternoster principle of continuously circulating conveyors are available for a wide range of applications.

Direct–contact heating (in an induction–heated mold, for example), is also an option, but often plays too much of a role in setting cycle time due to its relatively long heating cycles caused by insufficient contact at the start of the heating phase.

Most forming methods require Tepex® to be present as a consolidated panel. A (multiaxial) consolidated laminate, known as a stack or cross–ply, should first be made from the unidirectional tape, especially in the case of Tepex® UDea®. It is possible to do this using automated tape laying technology followed by consolidation.

Figure 6: Simplified illustration of the stacking process



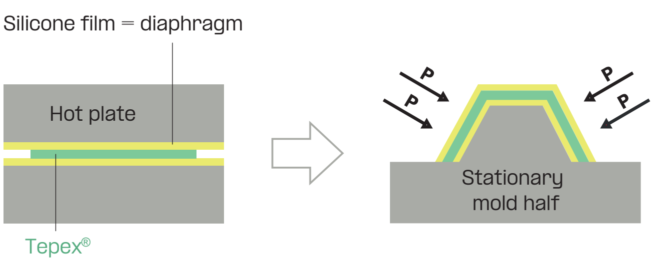
2.2. Forming behavior

There are numerous methods available for forming Tepex®. Which one to choose depends largely on component complexity and the quantity to be manufactured. The different methods are explained in brief below.

2.2.1. Forming with silicone or rubber stamps

In the diaphragm forming process, the oldest method of manufacturing thin–walled components from continuous–fiber–reinforced thermoplastics, the semi–finished product is placed between two highly elastic sheets and the entire assembly is heated by means of radiation or conduction to a temperature above the melting point of the matrix and then transported to the forming station. The press is closed, whereupon the diaphragms act as seals. The heated laminate package is placed on the forming mold (a positive mold) and then exposed to compressed air. An additional vacuum can be applied to the mold to support the forming process. The formation of smooth/defined surfaces is not possible with diaphragm forming owing to the relatively low pressures involved in comparison with other methods.

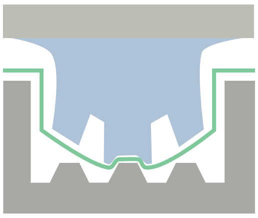
Figure 7: Simplified illustration of diaphragm forming with Tepex®



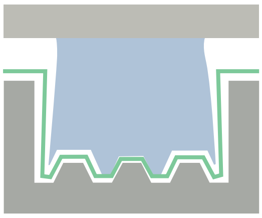
The advantages of this method are the low up–front cost and the possibility of forming materials of different thicknesses with one tool. The process requires relatively long cycle times and is better suited to simple component geometries, although minor undercuts are possible.

Alternatively, the tool used can be a negative mold. In that case, it is possible to carry out forming according to a similar principle – with the aid of a rubber stamp, for example. With this pressing method, the entire mold setup comprises a solid die (negative mold) and a stamp made of silicone or rubber. Closing the tool at a low pressure forms the Tepex® into a component.

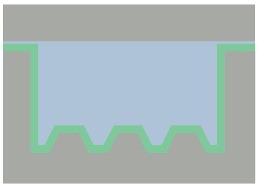
Figure 8: Simplified illustration of Tepex® being formed using a rubber stamp



1. Central bead formed



2. All beads formed



3. Completely formed

The high elasticity of the silicone/rubber stamp with simultaneous incompressibility enables sequential forming, which ensures the required even distribution of pressure during the forming process (see also Section 3). Adequate ventilation must be in place. Forming with silicone/rubber stamps is suitable for prototypes and small–series production owing to the low investment costs involved and the ease of optimizing the stamp. However, the method has proved effective for large–scale production of simple geometries as well.

With both variations of the method, surface quality is defined by the solid half of the mold on which the Tepex® is formed.

2.2.2. Forming with metal molds

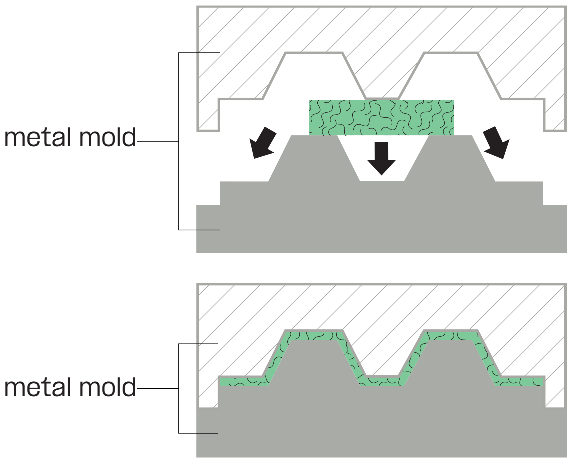
In most cases, Tepex® is formed using match metal molds. With methods of this type, both halves of the mold are made of metal, often steel, and are temperature controlled depending on the polymer in question (known as matched–metal molding). The cavity is a very important part of the mold design. The special forming mechanism involved with organo sheets means that there are some fundamental aspects to be taken into account. Refer to Section 3 for more information about this.

This forming method in conjunction with suitable automation allows for very short cycle times and a highly reproducible process. Furthermore, components manufactured in this way exhibit minimal warpage. The other side of the coin is that the process requires a bigger up–front investment and a more complicated design. It is therefore a method particularly suited to large–scale production.

2.2.3. Compression molding of Tepex® flowcore

As we mentioned earlier, Tepex® flowcore is reinforced with finite fibers measuring up to 50 mm in length and is therefore suitable for compression molding. It can be used to create even quite complex component geometries. It is also possible to mold ribs and functional elements. Compression molding is widely used in the plastics industry and is valued for its high reproducibility and short cycle times.

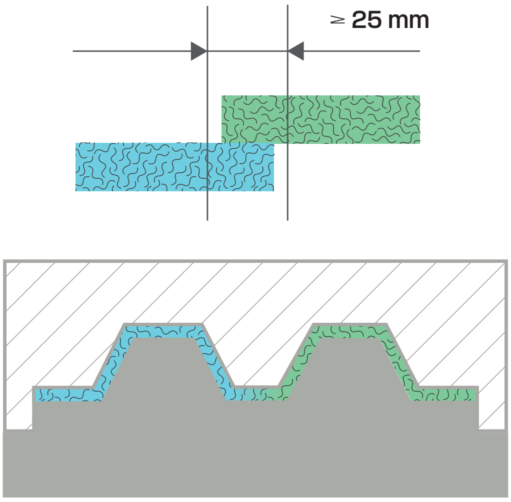
Figure 9: Compressiong molding of Tepex® flowcore



In a similar process to those used for the familiar GMT (glass–mat thermoplastics) and LFT (long–fiber thermo–plastics) thermoplastic extrusion materials, a precisely defined volume of Tepex® flowcore is first heated and then placed in a suitable position in the mold. The mold–ed part is formed, or the mold is filled, as a result of the mold being closed, causing the polymer melt to flow. Positive molds are usually used for this.

The flow properties of Tepex® flowcore make it possi–ble to combine multiple inserts into one component with much larger outside dimensions. For this, it is necessary to ensure that the flowcore inserts overlap in the mold across at least half of the fiber length. Because the maximum fiber length with Tepex® flowcore is 50 mm, that means that an overlap of 25 mm is enough to fulfill this requirement in every variant of the material.

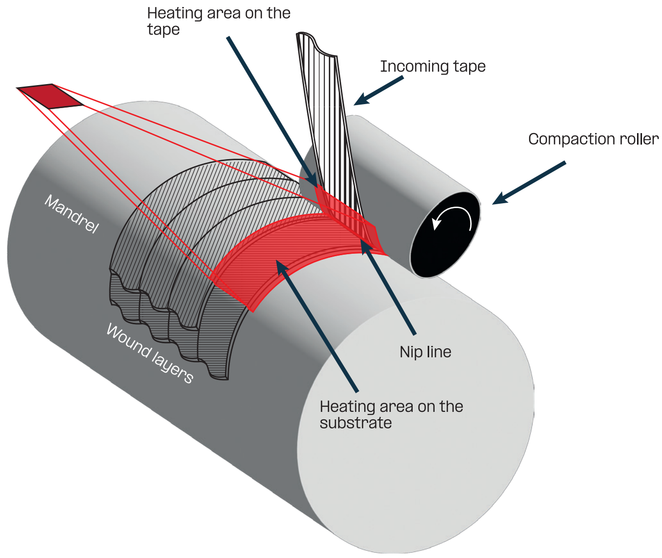
Figure 10: Overlap zones in impact extrusion



2.2.4. Winding Tepex® UDea®

During winding, the thermoplastic tape is routed via an automated, CNC–controlled winding head to a winding core or mold. During positioning, the targeted heating of specific areas by a laser melts the thermoplastic ma–trix. The malleable thermoplastic "prepreg" – material that has been pre–impregnated – is then placed on the winding core and routed around the core at the speci–fied angles according to the component design. The au–tomated process control enables the precise adjustment and monitoring of quality–defining parameters such as process temperature, contact pressure and the tape's initial tension. This means that component consolidation can be set during the winding process itself, removing the need for any post–treatment or post–consolidation of the wound component (e.g. in an autoclave, as in the case of thermoset wound components). Instead, the component is ready to use as soon as the winding pro–cess is complete.

Figure 11: Simplified illustration of the tape winding process



2.3. Combined technologies

The combination of Tepex® with short–fiber–reinforced or long–fiber–reinforced plastics with an identical or compatible matrix system and the methods used for processing – injection molding and compression mold–ing – also offers an excellent opportunity to use not only lightweight materials but also lightweight structural design; for example, injection molding

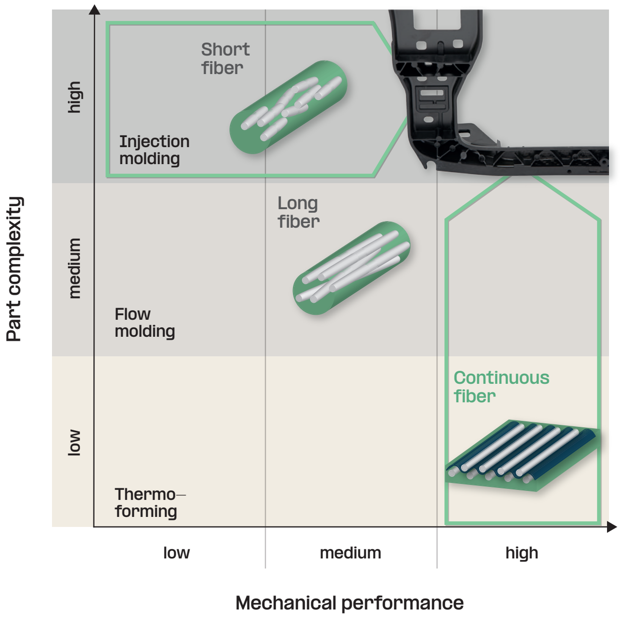
– reinforcing and stabilizing ribs
– load transfer elements
– functional elements
– contours at the edges of the component.

Suitable material selection and process management will result in a component with a material bond between the two components (see Figure 9).

This innovative process, outlined below, has its roots in a research and development project named SpriForm, funded by the German Ministry of Education and Re–search (BMBF). The technology has continued to evolve since then. KraussMaffei and Engel, both manufacturers of machinery, market this combined technology under the names "FiberForm" and "Organomelt", respective–ly. There are two main versions: a two–stage process (referred to in this brochure as insert molding) and a single–stage process (hybrid molding). Both methods share the following benefits:

– Greater design flexibility
– Option to integrate additional functions and thereby cut down on subsequent steps
– Combination of lightweight materials and design
– Short cycle times
– Reproducible and fully automated processes
– Available and manageable technical systems

Figure 12: Options for combining Tepex® with compounds



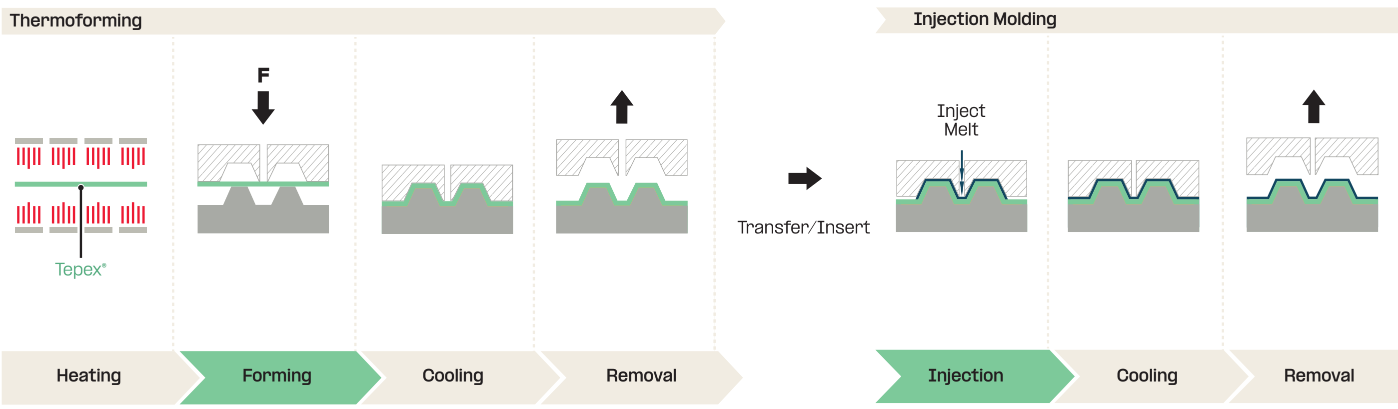
Irrespective of the technology chosen, it is essential to ensure a strong bond between the two components by means of heat sealing. This composite adhesion depends largely on the temperature of the composite (organic sheet or tape), the temperature of the molten material at the moment of injection and the injection pressure at the relevant position. These can be used to draw the following conclusions regarding process engineering, which can be confirmed by means of suitable tests.

1. The higher the temperature of the composite and the injected molten material, the better the adhesion. Because injection molding takes place at relatively high melting points and a contact temperature applies at the join site, composite temperatures below the melting point are usually also adequate.
2. The transfer time between composite heating and the forming stage should be as short as possible to prevent cooling. This applies as a general rule.
3. injection speed has a significant influence on composite adhesion. The higher the speed, the more shear force is introduced to the molten material and the lower the cooling effect, which has a positive impact on the heat–sealing process. This effect particularly occurs in areas far from the gate.
4. Higher dwell pressure is also good for bond strength.

2.3.1. Insert molding (in combination with injection molding)

With the insert molding method, forming of the composite and overmolding/injection with the short–fiber–reinforced or long–fiber–reinforced plastic take place in separate molds and machinery. To achieve a material bond or heat seal with the injected plastic material, it is advisable to heat the pre–formed component (insert) again before it is positioned in the injection mold. Only then will the best possible heat seal be achieved for both components.

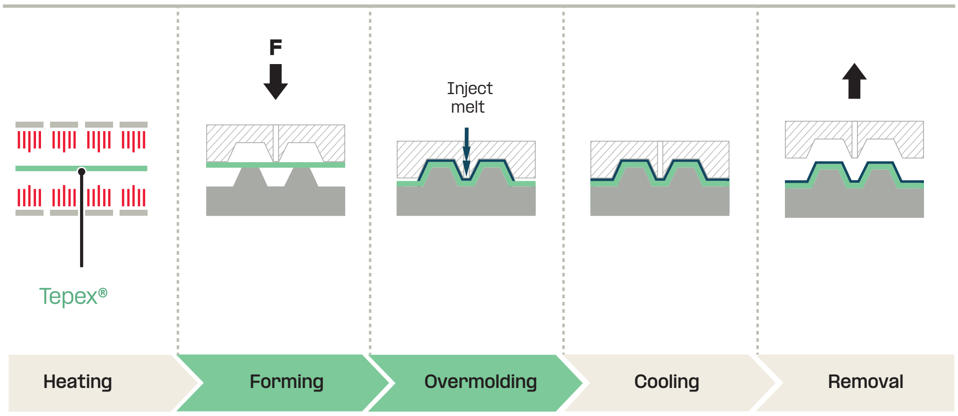
Figure 13: Insert molding with Tepex®



2.3.2. Hybrid molding (in combination with injection molding)

The situation is different in the case of hybrid molding in that the composite is formed alongside the injection process in the injection molding tool. The clamping unit of the injection molding machine acts as a forming press. This means that the tool has to perform various functions and therefore needs to be designed specifically for this process. Section 3 provides further information about the design. To manufacture off–tool parts without any finishing work, the semi–finished products are provided as near–net shapes, which are blanks made to be close to the final dimensions of the product. These blanks represent a version of the component to be manufactured that is suitable for drape forming, which can be calculated by means of a draping analysis (see also Section 6: "Design and calculation of components").

Figure 14: Hybrid molding with Tepex®



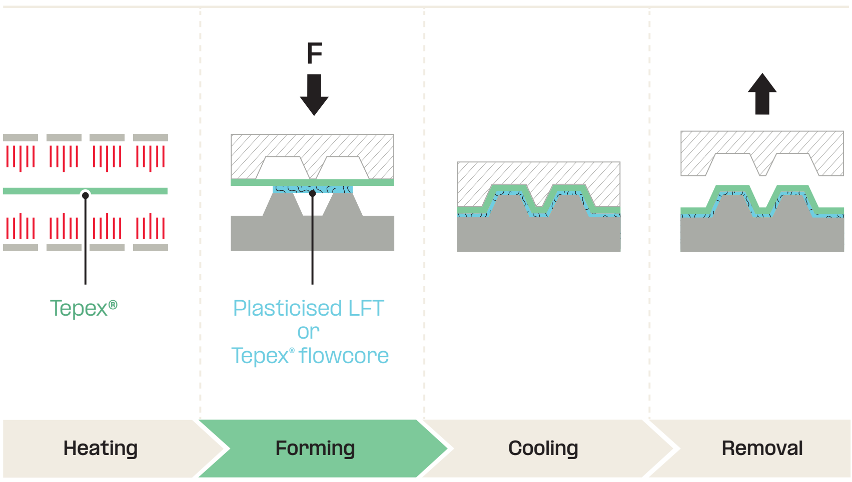
2.3.3. Compression molding (in combination with LFT compression molding)

LFT stands for long–fiber thermoplastics, which contain reinforcing fibers at least 4 mm long. In the direct version of the process, which is the most commonly used, the molding compound – consisting of fibers, matrix and any additives – is manufactured using extrusion technology upstream of the press. The resultant compound is then processed by means of impact extrusion with positive molds. The clamping pressure of the press, which is designed accordingly, induces the necessary flow in the molten material.

This process can be combined with pre–heated organic sheets for a simple method of manufacturing large, highly resilient and warp–free components in very short cycle times. One notable feature is the extremely high–impact resistance of components produced in this way.

This method can be used to process Tepex® flowcore instead of an LFT compound. It is also possible to used combined semi–finished products made from Tepex® dynalite and flowcore for further processing in compression molding.

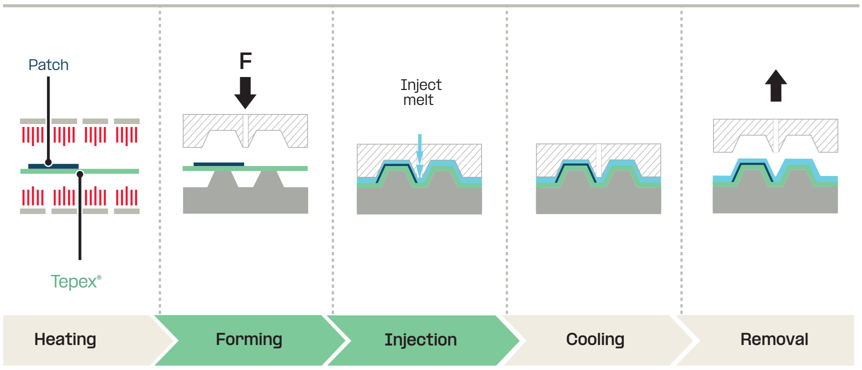
Figure 15: Tepex® hybrid molding combined with LFT or Tepex® flowcore



2.3.4. Patching (in combination with UDea® tape)

Patching refers to the local reinforcement of large molded parts. For example, a component such as an underbody protection will need higher strength in the vicinity of its fastenings to prevent bolts or rivets from being pulled out. Alternatively, there may be a very high localized load in a specific area of a component that necessitates additional reinforcement. In such cases, either a small insert made from Tepex® dynalite or a suitable prepared blank made from UDea® can additionally (or subsequently) be positioned in the mold. If a corresponding recess is provided in the mold cavity, an automated handling system can be used to ensure exact positioning so that the base body and the patch can be heated, positioned in the mold, formed and (if applicable) overmolded at the same time.

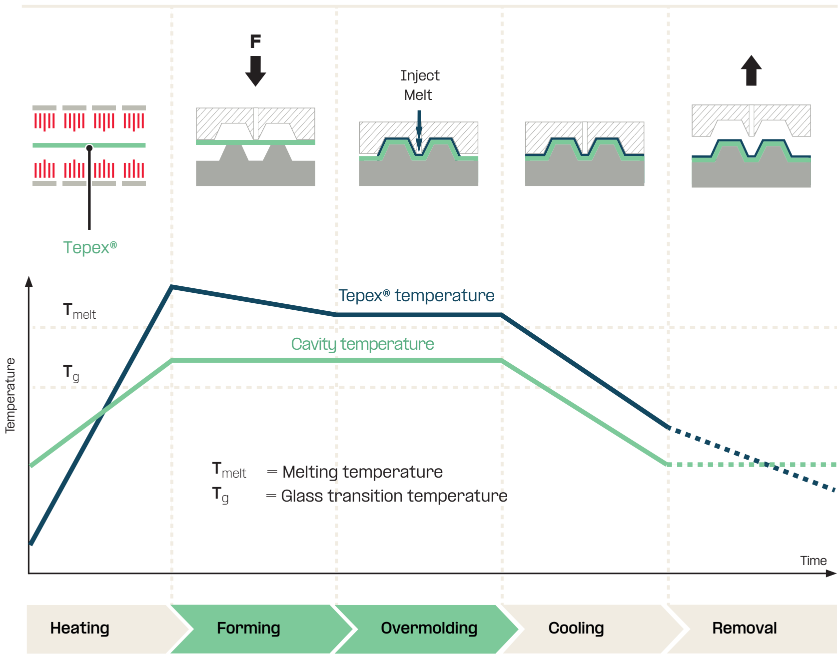
Figure 16: Patching of Tepex® UDea®



2.4. Variothermal process control

If necessary, it is possible to increase the surface quality of Tepex® components even further with the aid of vario–thermal process controll. With variothermal controll of the mold, the mold walls are temporarily heated to a temperature between the glass transition temperature and melting point of the plastic used. Only once the molded part is formed is the mold cooled down again. This increase in mold wall temperature delays the solidification of the molten material, allowing the surfaces of components manufactured using this process to develop effectively. Figure 17 shows how the process unfolds, including the temperature cycles for Tepex® and the mold wall for hybrid molding.

Figure 17: Variothermal process control with hybrid molding



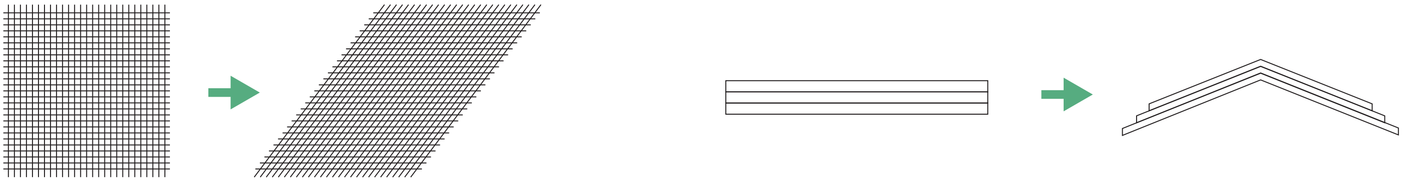
3. DESIGNING MOLDS AND *HANDLING SYSTEMS*

We have built up a wealth of experience in finding the best mold setups for processing Tepex® and coordinating the design of handling components to match. Envalior is ready to help customers with projects by deploying its engineering customer service team to advise on all aspects of mold design. In addition, there are now numerous machine–builders and mold–makers that offer custom solutions for processing thermoplastic composites. When it comes to designing and handling Tepex®, it is vital to possess a fundamental understanding of the forming mechanisms for continuous–fiber–reinforced plastics.

3.1. Draping of Tepex®

The specific forming behavior of Tepex® has a considerable impact on mold design. Forming, also known as draping, only rarely uses flow processes as in conventional plastics processing methods; instead, it is based primarily on forming of the semi–finished textile product.

Figure 18: Forming mechanisms for Tepex®; left: trellis effect; right: shifting of separate layers



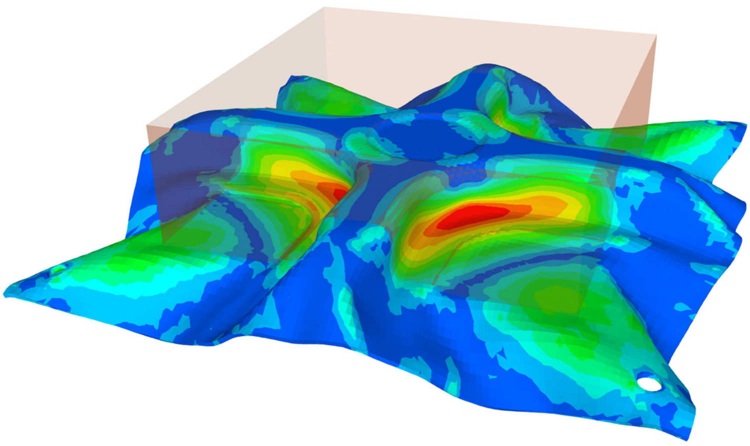
There are essentially two different drape forming mechanisms, as illustrated in Figure 18 (fiber elongation, stretching and slip not shown):

– Angle changes / fabric shear strain of the semi–finished textile product, also referred to as the trellis effect

– Shifting among separate layers, also known as interply shear (when the laminate has a multi–layered structure)

These two mechanisms applied individually or together allow for very high degrees of deformation. Consequently, more or less pronounced changes in fiber orientation relative to their initial state can be achieved in areas of the component with significant three–dimensional deformation. The initial and unavoidable consequence is that the material thickens, which needs to be taken into account in the design of the mold (see Section 3.3., "Designing the mold cavity"). Any further increase in draping may result in the textile becoming jammed, leading to undesirable wrinkling. A draping simulation can provide valuable insight into such critical degrees of forming, enabling suitable action to be taken to prevent detrimental consequences.

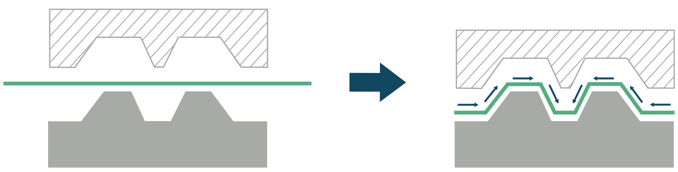
Figure 19: Results of a draping simulation (shear angle as a measure of fabric shear)



3.2. Notes on design regarding the special forming behavior of Tepex®

In addition to the forming mechanisms outlined above, knowledge of the special kinematics involved in the forming of Tepex® is a particularly important factor in designing and building molds. To ensure that the component can be molded reproducibly and evenly, it must be possible for the heated composite to slide unhindered from the outside to the center of the mold.

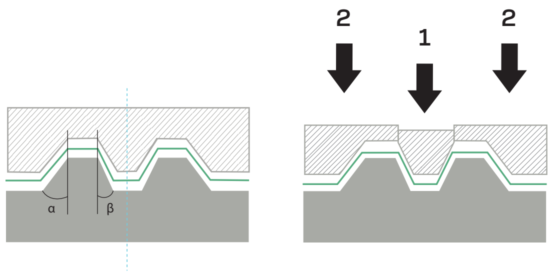
Figure 20: Sliding of Tepex® during the mold closing movement



In the case of more complex geometries, an unfavorable mold design may lead to tension between neighboring areas of the component, possibly resulting in the material getting caught and even tearing.

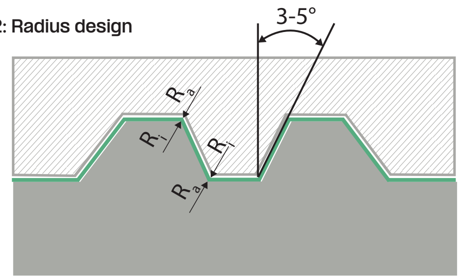
In such situations, a draping analysis, which is included in Envalior's CAE service, will identify relevant areas and provide useful information that will help with mold design. There are multiple possible approaches that can be employed to solve this problem through design. For example, the angles of the flanks extending from the center of the cavity to the edge of the mold can be increased, as shown in Figure 21. In addition, slides or moving stampls can be used to ensure that the material engages with the mold after a delay and thus is shaped one piece after the other (sequential forming). It may be necessary to check whether component sections are to be shaped at very shallow angles by active elements such as lateral slides.

Figure 21: Methods of preventing tension during forming (left: angle adjustment; right: integration of an advancing slide)



To ensure that components made from Tepex® can be effectively shaped as described but also quickly and safely removed from the mold, opening angles / draft angles of ≥ 5° are recommended for vertical areas of the mold, regardless of material thickness. Contours with draft angles of ≥ 2° are also possible in some cases.

Figure 22: Radius design



Wherever possible, the inner and outer radii of angular contours should be designed in accordance with the following rules, partly so that the fibers are not damaged during forming by excessively sharp mold edges.

- Inner radius Ri ≥ Tepex® wall thickness, but at least R1 (1 mm)
- Outer radius Ra ≥ inner radius Ri + Tepex® wall thickness

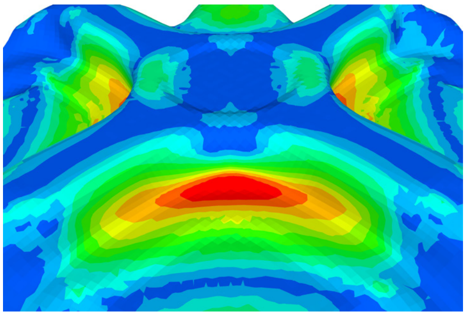
3.3. Designing the mold cavity

Tepex® is supplied fully impregnated and consolidated. This means that the individual fibers of the semi-finished textile product are enclosed by the thermoplastic matrix and the laminate contains almost no air pockets. When it is heated above the melting point of the thermoplastic matrix, Tepex® can increase in thickness by as much as 20 percent – it "lofts." The lofting process can essentially be explained as an increase in the volume of the plastic and the relief of residual stress in the semi-finished textile product as a result of the heating. During forming, the semi-finished product must therefore be re-pressed to the nominal wall thickness to create a smooth, compact surface without any imperfections and to achieve optimal component properties. The impregnation of the individual fibers is not lost during lofting, and so the process of re-pressing the material is also known as reconsolidation because it restores the consolidated state of the semi-finished product. The prevailing temperatures and pressures during forming are normally more than enough for this.

It is generally advisable to design the mold cavity in which Tepex® is to be formed to match the target dimensions for the component wall thickness, as with Tepex®, shrinkage is generally negligible. To ensure that pressure is transferred uniformly during forming, the mold cavity should also be designed to be 50–100 µm or so thinner than the mean Tepex® thickness as delivered.

Particular attention should be paid to the areas with high levels of draping (high shear angle). As outlined in previ–ous sections, this will result in increased thickness due to material accumulation. In spite of increased pressing forces, these can often not be re–pressed to the target dimensions; consequently, adjacent areas cannot be ex–posed to full pressure due to the mold being obstructed and thus cannot be shaped without flaws (see Figure 23). In such cases, the cavity will need to be designed to be thicker in those areas to ensure that pressure is distrib–uted evenly across the entire component.

Figure 23: Shear angle distribution projected on an actual component; the red area indicates localized thickening



A consistent and smooth surface on the manufactured component can generally be regarded as an indicator of good mold design, as it as a sign of pressure having been transferred uniformly from the mold to the component surface. However, a well–designed mold is not the only factor with a significant influence on surface quality, as process management also has a major role to play, affecting such aspects as:

– Temperature of the Tepex® insert

– Surface temperature of the mold (see also Section 2.4, "Variothermal process control")

– Pressing force

– Mold surface quality/condition

In summary, the precision of the cavity is of crucial importance to component shaping.

3.4. Integrating holes

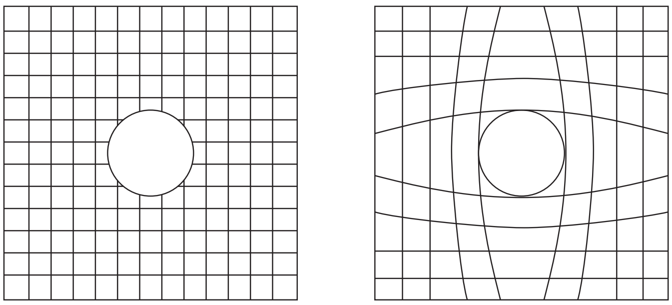
In principle, there are two ways in which holes and breakthroughs can be integrated:

1. Cutting or drilling holes during production of the Tepex® insert

2. Creating holes during forming by driving an awl through the fibers

The second variant appears advantageous in the case of high bearing pressures in particular, as it allows the forces to be diverted around the holes. Figure 24 provides a simplified illustration of this situation

Figure 24: Making holes: by cutting or drilling (left); by forming and driving through the fibers in the mold(right)



3.5. Notes on design for overmolding with Tepex®

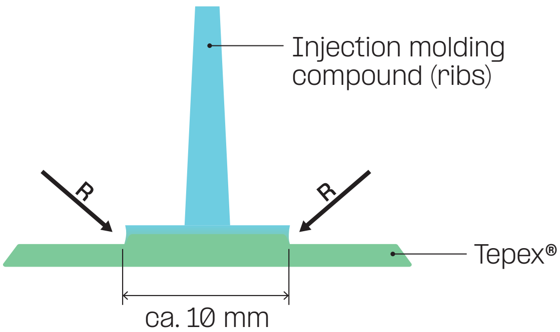
As explained in Section 2.3, by injecting a short–fiber–reinforced or long–fiber–reinforced plastic with an identical or compatible matrix like that of Tepex®, it is possible to achieve a material bond. Complex components can thus be designed with high strength and rigidity. Figure 25 shows a cross section of such a component. A typical rib structure is visible. This lends the component additional structural reinforcement and stability. There is also characteristic injection molding around the edges to provide a seal.

Figure 25: Example showing rib structure and injection–molded edges

3.5.1. Rib design

There are two main aspects to consider in the design of ribs for overmolding Tepex®. First of all, the base of the rib should cover a large surface, as shown in the illustration below. Experience shows that a width of approximately 10 mm is good, as it can be used to achieve a very good bond between the rib and the organic sheet – assuming optimal process management (see Section 2.3).

Figure 26: Simplified illustration of rib design

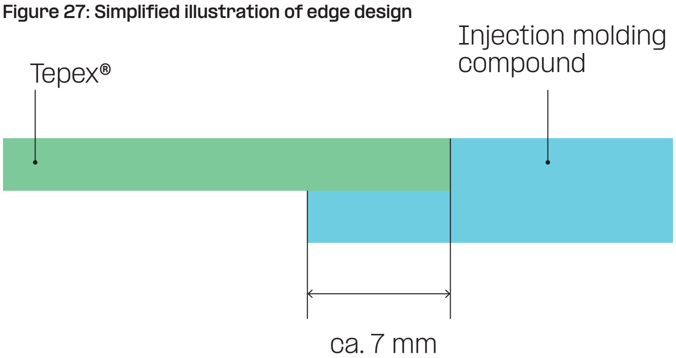


In addition, sharp edges should be avoided in the vicinity of the point at which the base of the rib joins the organic sheet. Rounded corners will prevent any damage to the fibers at the moment of the mold being lowered.

3.5.2. Designing the edges

In the process of designing load transfer and functional elements, it is recommended to use a combination of frontal and overlapping injection. The same applies to the design of the edges of a component, as shown in the following illustration. Frontal injection alone should be avoided if at all possible, as it can result in the unwelcome outcome of the Tepex® insert tipping over.

Figure 27: Simplified illustration of edge design



Coupling this approach with suitable process management makes it possible to manufacture an optimized composite.

3.5.3. Patching/overlapping with Tepex®

Based on tailored blank technology, there is also the option of combining various organic sheets in such a way that the component can be adapted to local loads by means of different sheet thicknesses. The composite sheets should preferably be heated separately first and only then put together either in or upstream of the mold and subsequently formed. The matrix being of the same type results in a material bond. See also Section 2.3.4 on patching.

3.6. General notes on design for handling Tepex®

The handling of the Tepex® insert plays a key role in ensuring good reproducibility of the manufacturing process and the component properties. When it leaves the heating station, it is hot and plasticized, meaning that it is pliable. These characteristics need to be taken into account in the context of transporting it to the mold, closing the mold and the actual forming process, as well as in the case of overmolding or back injection. The handling system needs to take on the following responsibilities:

– Gripping the insert securely during and after heating

– Avoiding any local cooling caused by the grippers

– Transporting the insert to the mold quickly over the shortest possible distance

– Handing the insert over to the mold precisely and reproducibly

Afterwards, the following need to be ensured in the mold:

– The blank is positioned with absolute precision and without heat loss

– The blank is cleared for forming during mold closure

The following types of gripper equipment are recommended for transportation between the heating station and the mold:

– Needle grippers, including stripper bushes (poked into composite sheet blank)

– Clamping pins, point grippers (clamping on both sides)

– Vacuum suction device

– Airflow/Bernoulli grippers (low pressure caused by airflow)

– Pins (holding the organic sheet blank in pre-made holes)

The following can be used to hold the blank in the mold:

– Needles for gripping the blank

– Swivel-mounted retaining fingers

– Clamping pins in both halves of the mold, used to hold the blank centrally between the two tool halves

– Vacuum suction device

To prevent Tepex® from cooling in the mold, the design of the transfer system should include a means of preventing premature contact with the relatively cold mold walls. Furthermore, these mounts must be designed to ensure that when the mold is closed, the Tepex® is held reproducibly in exactly the right position during forming without impairing the drape forming process.

4. JOINING METHODS FOR TEPEX®

Components made from Tepex® are often part of complex assemblies that, in extreme cases, may comprise a variety of materials such as steel, light metals such as aluminum and magnesium, short-fiber-reinforced or long-fiber-reinforced plastics or carbon-fiber composites. Rapid automated production of such assemblies to a high standard of quality and at low cost may require Tepex® to be joined to itself or with other materials. There are methods available for this purpose that have long been in use with thermoplastic components in industrial series production.

The different joining methods can be categorized according to their physical mechanisms of action, as follows:

– Material bonds (welding, adhesives)

– Frictional locking (bolting, pressing, riveting)

– Form fitting (snapping, catching, bracing)

There is also a distinction between detachable connections (bolts, studs, cotter pins) and non-detachable connections (adhesive, welds, rivets). Whereas welding can be used only for thermoplastic semi-finished products, with the aid of adhesives and mechanical joining, it is possible to join a wide range of material pairings – even to join plastics with totally different materials such as metals.

Specific joining processes should always be custom designed for the particular component and application in question. It may be advisable to consult adhesive producers, manufacturers of fasteners (bolts, rivets etc.), machine-builders (welding) and engineering service providers, who will be able to use their specialist expertise and experience to provide reliable assessments and designs for such processes.

4.1. Adhesives

Connecting components with adhesives is an established form of material bonding that enables even incompatible materials to be joined together. There is a multitude of adhesive systems on the market, some of which are tailored to specific material pairings.

When it comes to finding a suitable adhesive system for Tepex®, there are established systems that users can call upon. It is usually sufficient to have some knowledge of the composite matrix and the joining partner; adhesive systems customized specifically to Tepex® are not necessarily required.

Systems involving two-part epoxy adhesives, two-part acrylic adhesives and two-part polyurethane adhesives have established their credentials in series production as solvent-free, low-shrinkage adhesives.

The components need to be designed in a way that is suitable for the use of adhesives. The following types of stress on the adhesive bond may occur:

- Tensile shear: overlapping adhesive bonds enable the formation of large joining surfaces and thus the transfer of significant forces into the adhesive joint under relatively low shear stress. This is the type of load that should be targeted.
- Tensile stress: should be avoided, because the tensile strength of the adhesives is often lower than the strength of the joining parts.
- Peeling: peeling forces induce stresses perpendicular to the adhesive joint. This results in complex stress conditions and makes it difficult to estimate the amount of protection against destruction. If peeling forces are unavoidable, suitable measures should be taken to reduce them.
- Bending and splitting stresses: also to be avoided, because they can lead to significant stress peaks.

Cleaning and roughening the surfaces and/or activating or using special primers will improve adhesion.

Tepex® can also be joined with commercial structural adhesivesthat cure at cathodic dip coatig (CDC). This allows for a wider range of possible uses of the composite in lightweight design of vehicle body components, as no additional energy is required to heat and cure the adhesive in such applications.

4.2. Joining with injection molding

As outlined in Section 2.3, joining by means of injection molding is an efficient, versatile and widely used method of joining thermoplastic composites like Tepex®. If the injection-molded material and composite matrix are compatible in terms of polymer chemistry, the result will be a material bond with excellent adhesion. With this method, multiple Tepex® blanks can also be joined even with metal components to form complex assemblies in a single process step. Whereas the connection between the thermoplastic composite and the injection molding compound is generally a material bond, the connection with incompatible joining partners, such as metals, takes place either by means of form fitting (injection through breakthroughs or the polymer interlocking with surface features) or with the aid of processing agents. This means that adhesive agents can be used on metal sheets, enabling a secondary material bond between Tepex® and the metal.

4.3. Mechanical joining methods

Self-tapping screws and bolts with thread angles of 20° or 30°, as applicable, should be used for threaded fastenings for Tepex® components. Because inserting fasteners usually means having to pierce the fiber structures, either the fasteners should not be inserted into the primary load paths of the component or the fibers in the plasticized semi-finished product can be pushed aside so that they run around the hole into which the fastener will later be inserted without being destroyed (see Section 3.4, "Integrating holes"). Alternatively, load-transferring geometries, such as bolt dome heads, can be molded on during component manufacture.

As a general rule, forces should be transferred less via the bearing stress and more by suitable means to the semi-finished product or component. This can be accomplished by the use of large fastener heads and appropriate preload force.

4.4. Welding

Because Tepex® is based on a thermoplastic matrix, it is also suitable for use with appropriate welding methods. Welding uses mostly physical adhesion mechanisms to create a bond between two or more joining partners. This usually involves the joining partners being locally heated to a molten state and then brought into contact with each other under pressure before being cooled under the applied joining pressure. During the joining phase, the adhesion processes are activated and persist after cooling – generally reversibly.

There are many methods available, and they have been in widespread use in conventional thermoplastic processing for quite some time. The methods are suitable for large-scale production and have an extensive track record in the field of thermoplastic components. They vary in terms of weld strength, cycle time and suitability for use in large or small volumes.

Welding methods can be classified based on the means of heat input. Processes include:

- Heating by thermal conduction
- Heating by radiation
- Heating by friction
- Heating by convection

An excellent overview of the various welding methods and their suitability for thermoplastic fiber composites is provided (in German) in Handbuch Verbundwerkstoffe by Manfred Neitzel, Peter Mitschang and Ulf Breuer (published by Hanser Verlag).

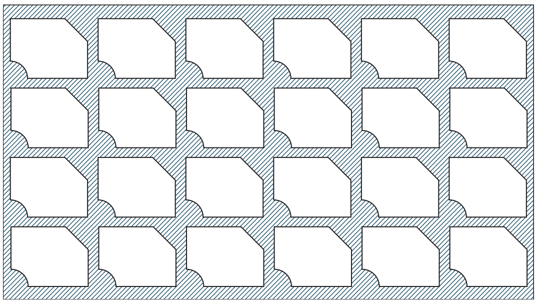
5. SUSTAINABILITY

Lightweight materials, which include all Tepex® products, help industry to be sustainable, make efficient use of resources and mitigate its impact on the climate. Using hybrid manufacturing technologies and designing hybrid components cut down on processing steps. With light-weight-specific design that makes use of the optimized distribution of forces via the long/continuous fibers in Tepex®, it is possible to conserve materials and feed-stocks in non-critical areas. The use of thermoplastics also allows the creation of integrated recycling loops.

5.1. Recycling Tepex®

Cutting out application-specific blanks is bound to produce a certain amount of offcuts, as shown in Figure 28. To minimize these offcuts, the relevant geometries are nested in the Tepex® semi-finished product – taking the necessary fiber orientation into account – in such a way as to achieve optimal yield. Particular attention should be paid during the development phase for Tepex® components to optimizing blank geometry with a view to reducing material waste. Even tiny adjustments can increase yield by considerable margins.

Figure 28: Example of offcuts produced after a blank is cut to the component geometry



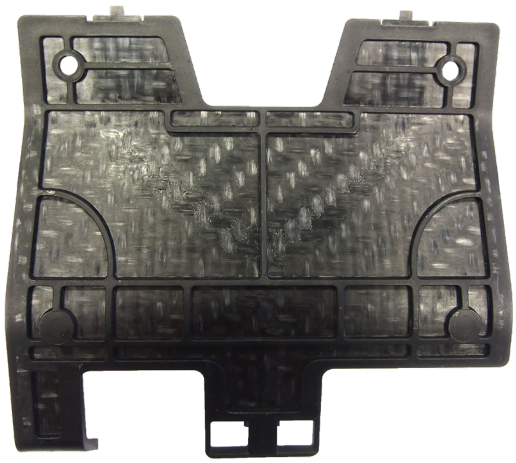
In the case of geometries with pronounced curves, which are difficult to nest, it is worth checking whether the component can be formed from multiple Tepex® blanks subsequently joined in the mold. This is often a way of making much more efficient use of material.

The unavoidable offcuts can be sent for recycling. Be-cause Tepex® is a fiber-reinforced thermoplastic, the following types of recycling can be used:

- Mechanical recycling
- Feedstock/chemical recycling, i.e. breaking the material down into its constituent parts by means of hydration, hydrolysis and pyrolysis or solvolysis
- Energy recovery, which involves recapturing the energy contained in the plastic

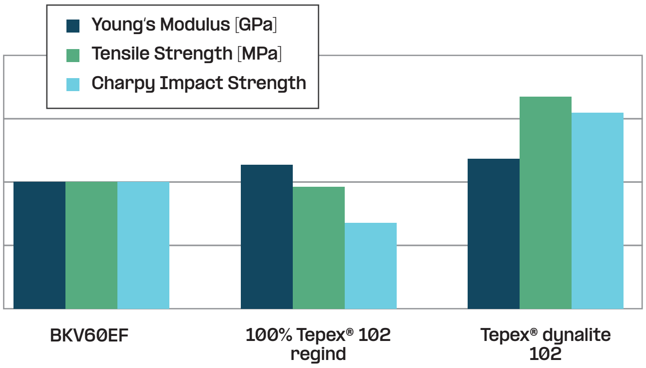
Mechanical recycling is the most efficient and sustain-able recycling method. With this process, the Tepex® off-cuts are first ground down to a defined particle size with the aid of granulators, single-shaft shredders or multi-shaft shredders. The resultant ground material can then be fed into a typical plastic processing operation. Owing to the low bulk density of the ground material, regulat-ed metering should be used in the case of high ground material content so as to prevent bridging in the hopper. However, if the ground material is mixed with granular virgin materials prior to metering, unmodified standard hoppers can be used for metering without any problems up to a ground material content of 20%.

Figure 29: Demonstrator component: formed Tepex® dynalite 104-RG600 overmolded with ground material from offcuts of the same material type



Mixing in unreinforced virgin materials enables the fiber content of the recycled material to be adjusted to a precise level so that it can be used to produce what is known as "regranulate." In the case of PP–based Tepex®, it is advisable to dilute the ground material to a maximum fiber content of 30–40 percent by mass, as this will make it easier to combine with commercially available short–fiber compounds. Tepex® can also be regranulated without first being diluted. The mechanical properties of the recycled material (strength, rigidity, toughness) are comparable to those of commercially available short–fiber–reinforced plastics with corresponding fiber contents.

Figure 30: Comparison of short–fiber–reinforced compound Durethan BKV60EF (PA6 with glass fiber content of 60 percent by mass) with Tepex® dynalite 102 (PA6 + glass fibers) and its recycled material (each with glass fiber content of approximately 65 percent by mass) – standardized figures



Solvolysis uses a suitable solvent to separate the fibers from the matrix material, which makes it a good process for recycling Tepex®. After solvolysis, the recovered raw materials (fibers and matrix polymers) are present but separate and, following suitable reconditioning, can be fed back into the Tepex® manufacturing process. The solvolysis process therefore enables all precursors to be recycled, thus creating a raw material cycle that should ideally not result in any deterioration in material properties (e.g. long fibers being reduced to short fibers). In the case of pyrolysis, in contrast to solvolysis, the matrix material is removed from the reinforcing fibers by a thermal process and converted into pyrolysis oil. This pyrolysis oil can, in turn, be used for energy recovery or to manufacture new plastics.

If polymers of the same type are used for the Tepex® matrix and the injection–molded material during component processing, the methods described above can also readily be applied to end–of–life waste – in other words, recycling these components once their service lives have expired.

5.2. Carbon footprint of Tepex®

To quantify the impact of Tepex® products on the environment, the manufacturing process is subject to ongoing analysis and assessment as part of environmental and energy management. One key indicator in this context is the carbon footprint for products.

The carbon footprint for Tepex® products is calculated according to the principles of ISO 14040 and ISO 14044 and is measured in kg CO2e [kilograms of carbon dioxide equivalent] per kg of Tepex® product. All material flows for the raw materials used throughout their life cycles, right up to the point at which the Tepex® product leaves our factory gates for sale, are factored into the assessment. This is known as a cradle–to–gate assessment. Because the Tepex® manufacturing process is virtually identical for all products in the range, the input and output flows can be handled uniformly for all Tepex® products in the assessment. The offcuts produced during component manufacture are recognized in the assessment as secondary products by means of economic allocation. The carbon footprints declared by the suppliers of the respective raw materials are used and weighted averages are calculated based on the purchase volumes. If the suppliers are unable to provide any primary information, data can be obtained from the ecoinvent database or estimates based on available reference documentation.

In any analysis of a specific Tepex® type, it is the raw materials used that have the biggest impact on the carbon footprint of Tepex®. For example, using bio–based raw materials, such as flax fibers or PLA, can reduce the carbon footprint of a Tepex® semi–finished product by more than 50 percent compared with a version made from glass fibers and PP.

The carbon footprints of many Tepex® types are available to view via the Envalior Plastics Finder (www.plasticsfinder.envalior.com). The increasing availability and quality of data mean that it is possible to provide component–specific carbon footprints, enabling sustainability to be taken into account right from the early stages of component and process design.

Figure 31: Comparison of carbon footprints of various Tepex® types

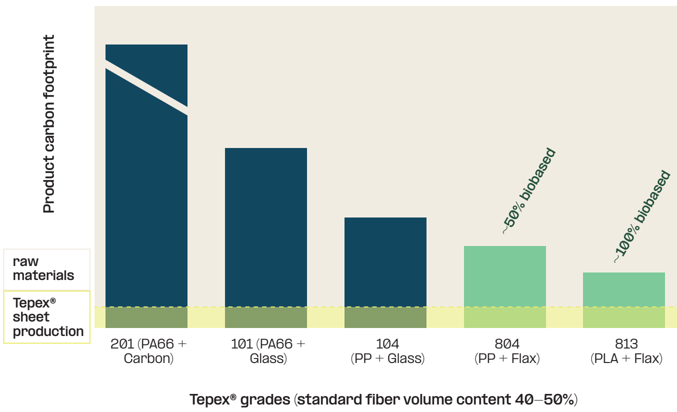


Figure 32: Distribution of process emissions, CO2e of raw materials, the disposal of waste and other equipment and packaging

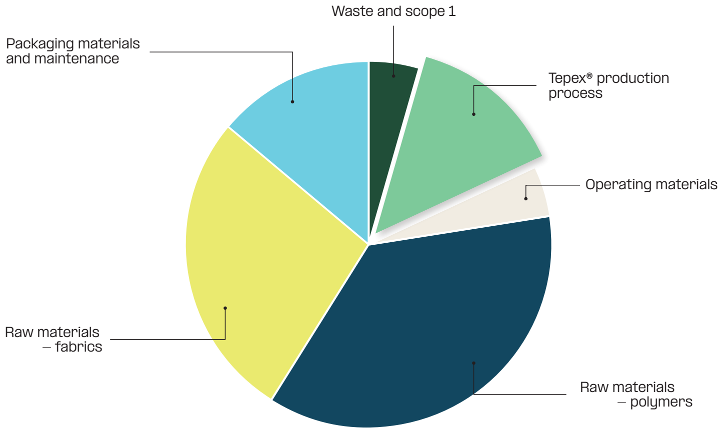


Figure 33: Value chain: Tepex® → ground material → regranulate → component made from recycled material

6. DESIGN AND CALCULATION OF *COMPONENTS MADE FROM TEPEX®*

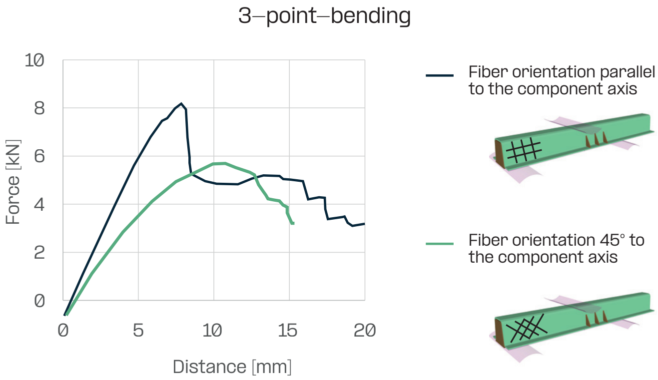
Tepex® offers designers an enormous amount of freedom in terms of the load–appropriate design of lightweight components that can be subjected to significant stresses. Their properties depend on the thermoplastic used for the matrix, the type of continuous fibers (glass, carbon, etc.) and the type of reinforcement used (unidirectional, bidirectional, multiaxial).

One of the most important factors in computational design is the directional dependence (anisotropy) of the mechanical properties resulting from reinforcement with continuous fibers. Unidirectional continuous fibers embedded in a thermoplastic matrix show the properties of the fiber material in the direction of the fibers (unidirectional) and provide more information about the properties of the matrix perpendicular to the fibers (bidirectional and tridirectional).

The fiber length matches the component length in components made from Tepex® dynalite, semipreg or UDea®. Wherever possible, the designer should therefore orient the fibers in the direction of the forces acting on the component so that the forces are distributed between points of application via the continuous fibers.

However, a more complex stress situation in the component (e.g. combined shear and tensile/compressive stress in a curved profile) may call for a combination of different fiber orientations. A symmetrical layer structure helps in designing a low–warpage component. Furthermore, the forces should be absorbed across as large an area as possible to prevent stress peaks and notch effects and to ensure that multiple fiber rovings are always being loaded at any given time.

Figure 34: The impact of fiber orientation on component behavior



6.1. FEM calculations: prerequisites and specific characteristics

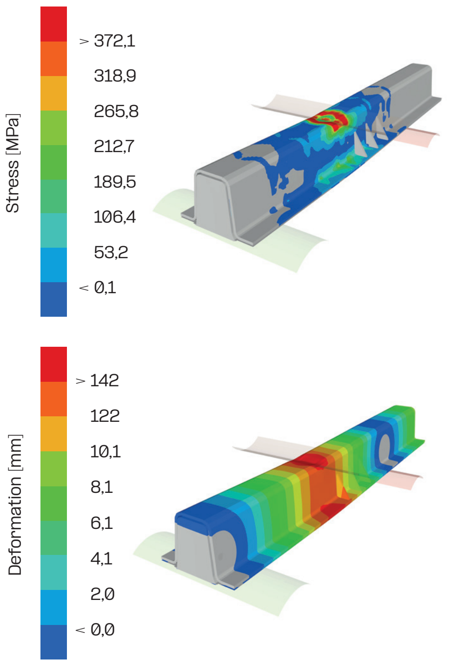
The computer-aided engineering (CAE) of components made from Tepex® is essential for achieving short development times, cost-effective manufacturing processes and component design optimized to the load cases. In this context, "engineering" expressly refers both to the manufacturing process and to the mechanical behavior of the component and the correlation between manufacturing and component properties.

As previously explained, the property of the semi-finished product most significant for engineering design is anisotropy, or directional dependence. The morphology of the reinforcing fabric also results in dependence on the location in the through-thickness direction (layer structure) and drapability for the manufacturing process. Dependence on temperature and, in some cases, moisture content are derived from the matrix properties. In certain circumstances, there may also be relatively significant differences between tensile and bending properties arising from the layer structure.

Both the manufacturing process and the component behavior can easily be described with commonly used finite element methods (FEMs) and widespread computational programs (solvers), with accuracy and forecast quality depending partly on the modeling approach and the scope of the underlying measurement data, but also on the matter of which load cases are to be analyzed.

To allow the manufacturing process, the resultant fiber orientation and the component properties, including fracture behavior, to be forecast to a sufficient degree of certainty, Envalior has developed tools and material models based on Abaqus, an FE solver, that describe the specified properties and influencing factors and thus can be used directly in the development process for Tepex® components.

Figure 35: Stress distribution and deformation in a three-point bending test with a standard structural beam



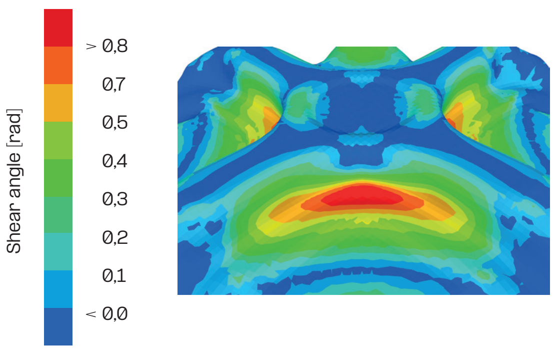
6.2. Draping simulation

A forming or draping simulation serves two separate purposes:

- Determining the distribution of the local fiber orientations and shear angles in the fabric. These, in turn, are needed in the mechanical calculation to consider the anisotropic material behavior. This calculation is often required early in the project, during the concept design phase, to assess the mechanical aspects of different proposed concepts. The simulation of fiber orientations therefore needs to be a quick and simple process and to require as little information as possible about the mold, as much of this will not yet be available at this stage. Envalior uses an FE-based calculation method for this – one that is very fast, which means it can define the appropriate blank and the distribution of orientations for a given Tepex® geometry during the design process. The method is not exact, but adequately precise on the whole (one-step draping).
- Visualizing the entire draping process, taking into account blank geometry, mold geometry, slides, needle grippers, handling system, etc. This should involve visualizing the task and process, identifying potential errors at an early stage, devising suggested improvements and estimating process reliability. Calculating fiber orientation is somewhat less important in this process. The complete draping study should ideally be performed if the component geometry is defined and a slide design and mold data (at least the mold surfaces) are already present but there is still some degree of freedom.

The simulation model developed by Envalior for the draping of Tepex® components is based on the Abaqus FE solver. It takes into account the fact that thermoplastic woven-fabric-based composites cannot undergo plastic deep drawing but are instead converted from a flat shape to the three-dimensional geometry of the component by means of fabric shear (using the trellis effect). If the shear required for forming is so great that the fibers interlock, the material will deflect in the normal direction, creating creases. This effect can also be simulated in the computational model.

Figure 36: Shear angle distribution in a baffle plate component



6.3. Material data and models for in–house component design

Envalior assists customers with component development using simulations of component and process properties in collaborative development projects. However, it is also important to be in a position to supply customers with tools that they can use to design new applications using Tepex® in the context of their own in–house CAE work–flows.

In contrast to the computation of metals, material modeling of thermoplastic composites like Tepex® – comprising the material model, the interface for glass fiber orientation and suitable failure models – is not yet common practice. This is part of the reason that Envalior has been endeavoring to pursue its own approaches to materials from a very early stage.

Depending on the application and the assignment in question, however, Envalior can provide material cards for the Tepex® material family that can be used with the most popular CAE programs; for example:

– Linear orthotropic material cards for linear rigidity, noise, vibration and harshness (NVH), and static tests, e.g. in Abaqus, NASTRAN, OptiStruct, LS–DYNA

– Non–linear orthotropic material cards for LS–DYNA and Abaqus

In addition to the material description, a neat description of the distribution of glass fiber orientation is necessary in all cases. This can be determined using appropriate commercial approaches or, upon request and on a proj–ect–by–project basis, stipulated by Envalior for a given model (one–step draping).

7. ENGINEERING SERVICES THAT COVER *THE ENTIRE DEVELOPMENT CHAIN*

Envalior's engineering services are grounded in a vast wealth of expertise in materials, composite technologies, simulation methods, component testing, processing and manufacturing. We apply this expertise in working with our customers.

Engineering services for Tepex® include:

– Assisting with choosing materials given component requirements

– Providing tailor–made polymer types for insert mold–ing, hybrid molding and compression molding process–es

– Testing materials to identify key material characteris–tics for mechanical structural analysis and component design

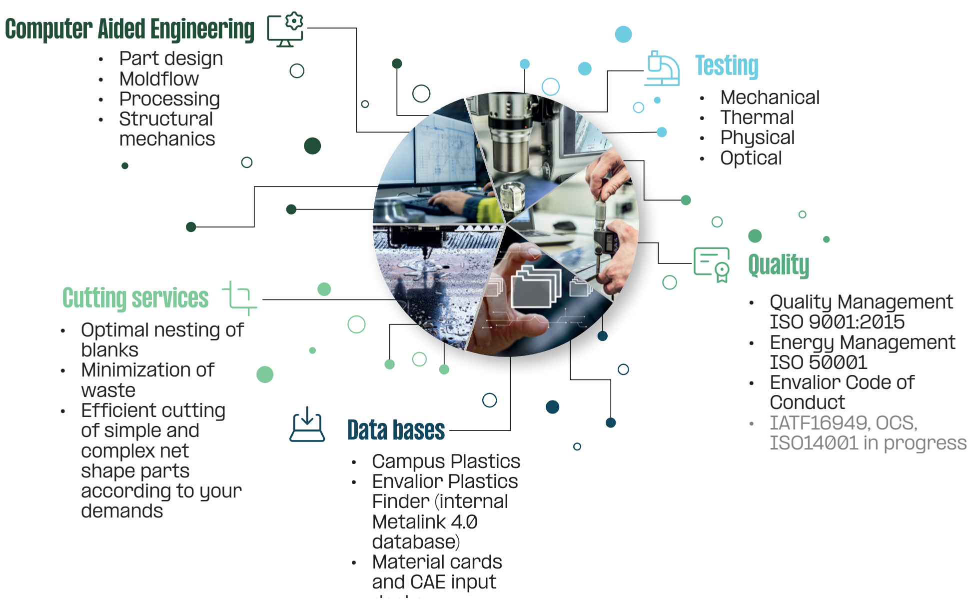
– Simulating the forming (by draping) of Tepex®

– Running integrative simulations to ensure that the de–signs of continuous–fiber composite components are suitable for the loads they will need to withstand

– Simulating customer manufacturing processes on our fully automated demonstrator cells, which realisti cally reproduce series production conditions, to es–tablish process parameters and for quality assurance and improvement

– Performing mechanical component tests, climatic tests and other such assessments

– Providing on–site assistance with mold validation and process optimization



8. ACKNOWLEDGMENTS

The following companies and universities have kindly supplied images and further information for this brochure:

– ENGEL AUSTRIA GmbH, Ludwig–Engel–Strasse, 14311 Schwertberg, Austria

– Rosenheim University of Applied Sciences (Prof. Schemme, Prof. Karlinger)

– Paderborn University (Prof. Moritzer, Prof. Schöppner, Prof. Obermann)

– Georg Kaufmann Formenbau AG, Rugghölzli, 5433 Remetschwil, Switzerland

– KraussMaffei Technologies GmbH, Krauss–Maffei–Strasse 2, 80997 Munich, Germany

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