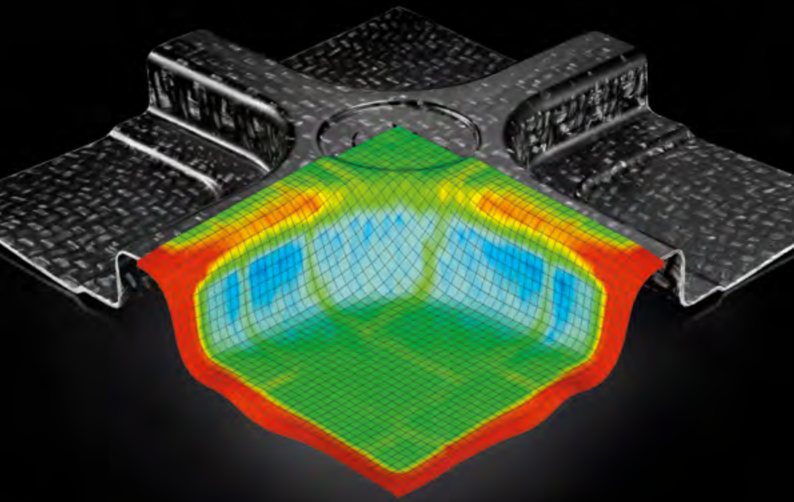
QUALITY PERFORMS.



Information for processors

Tepex®

QUALITY WORKS.

LANXESS
Energizing Chemistry

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1. ABOUT TEPEX®

Our thermoplastic high-performance composite Tepex® has established itself as a lightweight construction material for a wide variety of applications in large-scale series production. Its consistent quality and the thermoplastic matrix make it ideal for fully automated and reproducible manufacturing and processing operations. Tepex® is used in automotive engineering, the sports industry, consumer electronics and various other sectors.

Tepex® is a group of composite semi-finished products that are fully impregnated, consolidated and plate-shaped. They are made of high-tensile continuous fibers (or long fibers in the case of Tepex® flowcore) and a thermoplastic matrix. These composite sheets can be processed into complex components in short cycle times through heating and subsequent forming. Continuous fibers are mainly glass and/or carbon fibers in the form of fabrics, inlays or other semi-finished textile products. Matrix materials are thermoplastics such as polypropylene, polyamide 6, polyamide 66, polyamide 12, polycarbonate, thermoplastic polyurethane and polyphenylene sulfide. The strengths of Tepex® can be summarized as follows:

- High stiffness
- Very high strength
- High lightweight construction potential thanks to low density
- Very short cycle times in component manufacturing
- Thermoplastic matrix enables overmolding and welding
- Excellent design flexibility
- Solvent-free
- Recyclable
- Very good energy absorption properties
- Low coefficient of thermal expansion
- Good dimensional stability and chemical and corrosion resistance

This brochure offers an overview of the structure of Tepex®, its properties and its processing options. It also presents our HiAnt® services, which we use to provide you with support in all stages of developing and manufacturing Tepex® components.

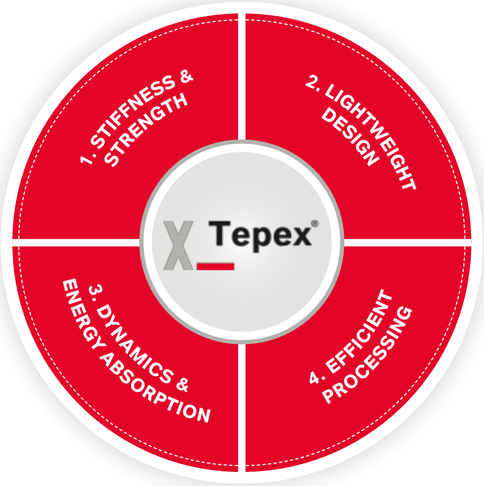
1.1 Matrix systems

Only thermoplastics are used as a matrix material for Tepex®. Their properties are particularly beneficial for processing. Thermoplastic matrices produce very short cycle times, while work hygiene is not critical. Thermoplastic-based fiber-plastic composites can also be combined with other thermoplastics with the same matrix and their processing methods. Design freedom for components can thus be increased significantly.

There is a widespread misconception that matrix materials are only used as an adhesive for reinforcing fibers while the actual composite properties are determined solely by the fibers.

The matrix system performs key functions:

- Transmitting forces into the fibers
- Transferring forces from fiber to fiber
- Protecting fibers against environmental factors
- Fixing fibers in the required geometric arrangement
- Absorbing mechanical loads, particularly high loads perpendicular to the direction of the fibers and shear loads



The following thermoplastics are used as standard for Tepex®:

- Polyamide (PA) 6, 6.6 and 12
- Polypropylene (PP)
- Thermoplastic polyurethane (TPU)
- Polyphenylene sulfide (PPS)
- Flame-retardant polycarbonate (PC fr)

1.2 Reinforcing fibers

As with all other fiber-plastic composites, Tepex® fibers need to absorb the loads on the component. To do this, they need to offer high stiffness and strength and the lowest possible density. Experience shows that most materials exhibit much better mechanical properties as fibers than in compact form. Glass and carbon owe their excellent credentials as reinforcing fibers to this paradox although they are not actually considered to be conventional structural materials.

1.2.1 Glass fibers

A glass fiber is an inorganic fiber whose high strength is based on the strong covalent bond (atomic bond) between silicon and oxygen (SiO_2 = quartz). Glass fibers are created from a melt that is cooled quickly so as to prevent crystallization and produce a three-dimensional network with an amorphous structure. Glass fibers therefore have isotropic properties.

Summary of glass fiber properties:

- Good cost-effectiveness with excellent mechanical properties
- Very high tensile and compressive strength
- Outstanding thermal and electrical insulation
- Completely non-combustible
- Very low moisture absorption
- Resistant against deterioration

Various types of fiber are available depending on the chemical composition, with E-glass being by far the most commonly used, also for Tepex®. Glass fibers have a diameter between 9 and 24 µm. The fineness of a glass fiber yarn or roving (strands of parallel continuous fibers), referred to as the titer, is given in tex (1 tex = 1 g/1000 m).

This parameter is a measure of the diameter and number of individual filaments in a glass fiber strand (yarn or roving). Fine types with a titer > 300 tex are generally described as filament yarns, while types with a titer > 300 tex are termed roving yarns. The titer of the fibers used in Tepex® are shown in the corresponding data sheets.

1.2.2 Carbon fibers

Carbon fibers are industrial fibers manufactured in a temperature range from 1,300 to 3,000 °C from a precursor (usually PAN fiber) and which have a carbon content between 92 and 99.9 % by wt. Carbon fibers are made up of individual layers (graphite structure). Their high strength and high modulus of elasticity are based on the strong covalent bond (atomic bond) between the individual carbon atoms in these layers. By contrast, the bonds between the individual layers are weak, with the result that properties perpendicular to the direction of the fibers are less pronounced. Carbon fiber stands out from all reinforcing fibers due to its extreme properties.

Summary of carbon fiber properties:

- Very low density
- Extremely high strength and very high modulus of elasticity
- Virtually linear-elastic properties
- Pronounced anisotropy
- Very low coefficient of thermal expansion, actually negative in the direction of the fibers
- Resistance to most acids and alkalis, tolerability in the human body
- Good electrical conductivity

Various types of carbon fiber are also available, and these may vary significantly in their mechanical properties. The most economically attractive fiber and the one most commonly used for Tepex® is high tensile fiber, which has very high strength and good stiffness. Carbon fibers have a diameter between 5 and 10 µm. As with glass fibers, carbon fibers are usually supplied as a continuous tow or roving wound on a coil.

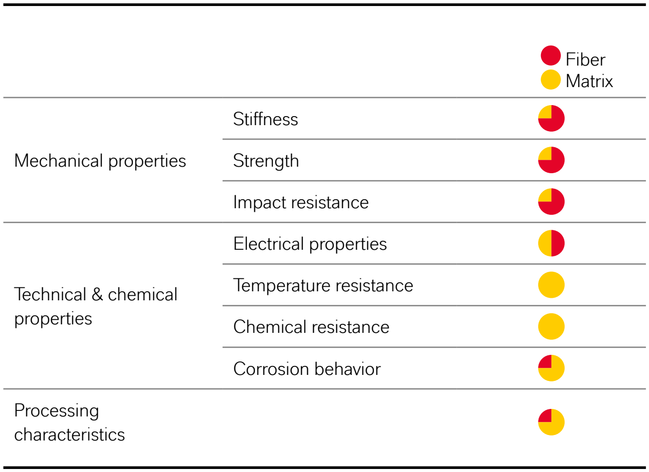
These tows consist of a number of individual filaments. The number of filaments in a tow is indicated by the K number (1K = 1,000 filaments/tow). Carbon fibers with a K number greater than 24 are referred to as "heavy tows."

1.3 Fiber-matrix adhesion and division of tasks between fiber and matrix

A composite only has optimum properties if the forces occurring are transmitted to the fibers and can be transferred from fiber to fiber. This requires a good bond between the fiber and matrix. In Tepex®, optimum bonding of the fibers to the matrix is always ensured by the targeted selection of a finish adapted to every plastic and applied to the fibers after manufacture, and – where necessary – by adding a bonding agent to the thermoplastic.

The division of tasks between fiber and matrix can be summarized as follows:

Figure 1: Illustration of the relevance of the components in the composite



		● Fiber ○ Matrix
Mechanical properties	Stiffness	◕
	Strength	◕
	Impact resistance	◕
Technical & chemical properties	Electrical properties	◑
	Temperature resistance	○
	Chemical resistance	○
	Corrosion behavior	◔
Processing characteristics		◔

It is worth underlining that the processing properties are determined almost exclusively by the matrix material. This will be examined in more detail in the following sections of this brochure.

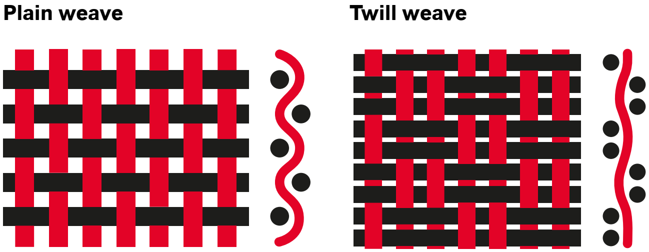
1.4 Semi-finished textile products

Special semi-finished textile products are used in producing fiber composite materials to optimize their design with regard to the necessary fiber orientation and to ensure efficient and reproducible component manufacturing. Primarily three different types of semi-finished textile products are used for Tepex®:

- Textiles with 0/90 degree fiber orientation:
  Bidirectional fabrics
- Textiles with unidirectional fiber orientation:
  Unidirectional fabrics or inlays
- Textiles with quasi-isotropic properties:
  Random fiber mats (nonwovens)

The fabrics are flat materials made up of warp and weft threads crossing at right angles, giving a bidirectional reinforcing effect at 0 and 90 degrees. Various types of weave exist for fabrics, with plain weave and twill weave usually being used for Tepex® (Figure 2). Twill weaves are a good compromise between achievable mechanical properties, formability and handling, which is why this weave type has become widely established in fiber composite technology. However, plain weaves are also used for many applications due to their ease of handling.

Figure 2: Diagram of a plain weave (left) and a twill weave (right)



If fabrics have a very high proportion of warp and weft threads, they are referred to as unidirectional fabrics and have a reinforcing effect mainly at 0 or 90 degrees.

An inlay is referred to as a nonwoven if it consists of one or more layers of parallel stretched threads. The reinforcing direction can be set within certain limits in almost any way using this semi-finished textile product.

The various types of reinforcement are also shown by the Tepex® code:

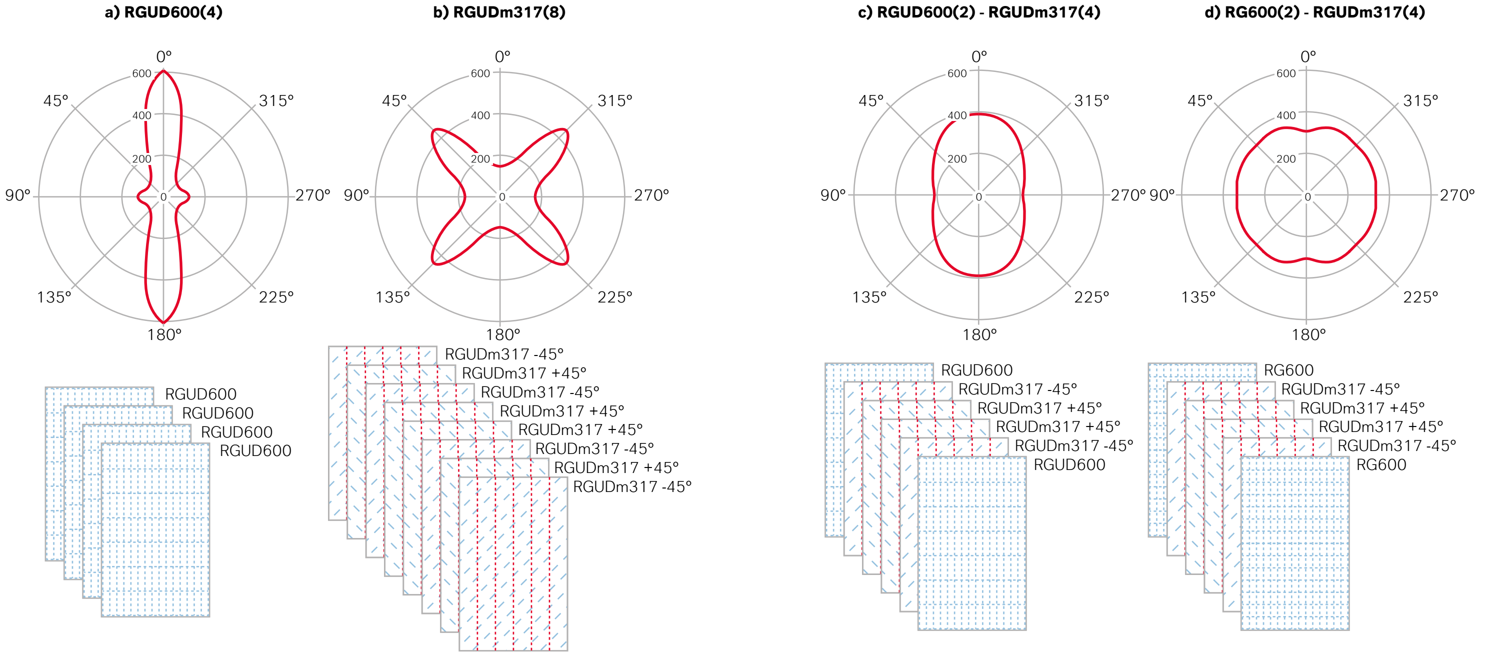
- C: **c**arbon fabric
- RG: **r**oving **g**lass fabric
- FG: **f**ilament **g**lass fabric
- CUD: **c**arbon fabric **u**ni-**d**irectional
- RGUD: **r**oving **g**lass fabric **u**ni-**d**irectional
- RGUDm: **r**oving **g**lass fabric **u**ni-**d**irectional, suitable for **m**ultiaxial structures

1.5 Tepex® laminate structures

In very rare cases, fiber composite structures are only subjected to unaxial stress, so that just one fiber direction is needed. The frequently multiaxial stress on the material thus usually calls for multiple fiber orientations, resulting in various laminate structures (multilayer composites).

In principle, all the above-mentioned semi-finished textile products can be combined in Tepex®. This offers designers the opportunity to configure the laminate to meet the specific load requirements. As well as conventional fabric fiber-reinforced laminates, this also enables the production of multiaxial structures and quasi-isotropic properties, as shown by the examples in Figure 3.

Figure 3: Examples of laminate structures with Tepex® (strength of a glass-fiber-reinforced PA6 as a function of the angle, displayed as a polar graph incl. the relevant laminate structures)



a) RGUD600(4)

b) RGUDm317(8)

c) RGUD600(2) - RGUDm317(4)

d) RG600(2) - RGUDm317(4)

1.6 Tepex® family

1.6.1 Tepex® dynalite

Tepex® dynalite materials consist of one or more layers of semi-finished textile products with continuous fibers embedded in a matrix of industrial thermoplastics. This grade is fully impregnated and consolidated. All the fibers are thus sheathed with plastic, and the material does not contain any air pockets. Tepex® dynalite therefore provides maximum strength and stiffness combined with very low density.

1.6.2 Tepex® optilite

Tepex® optilite is tailor-made for applications that require an esthetically appealing design and minimum thickness alongside maximum strength and stiffness. Tepex® optilite can be adapted to specific design requirements in terms of color and fabric architecture.

1.6.3 Tepex® flowcore

The fibers in Tepex® flowcore have a finite length, making this material suitable for flow-molding and thus enabling greater design freedom. Here, too, the fibers are fully impregnated and consolidated. The flowcore family also includes structures consisting of a combination of continuous (Tepex® dynalite) and long fibers (Tepex® flowcore). Typically, the continuous fibers are placed on the outside of the laminate, while the long fibers are placed in the center. This produces a fiber composite with maximum flexural strength that also supports molding of complex components.

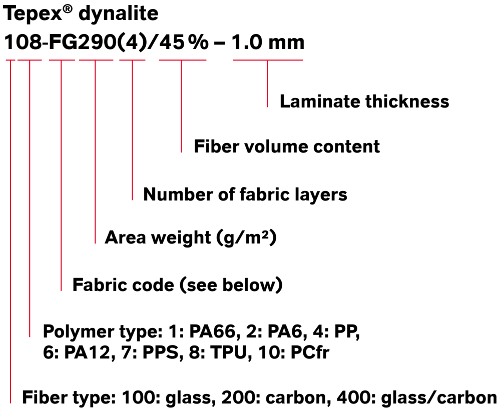
1.7 Nomenclature

A fiber composite is described unambiguously with the following information:

- Type of fiber (glass, carbon …)
- Type of semi-finished textile product (fabric, inlay …)
- Plastic (PP, PA6 …)
- Number of laminate layers
- Fiber volume content
- Direction of fiber orientation

As Tepex® is fully impregnated and consolidated, this makes it possible to calculate all other values such as laminate thickness and fiber content by weight. All relevant information can be derived from the Tepex® material code:

Figure 4: Breakdown of the Tepex® material code



Fabric code:
FG = Filament glass
FGAL = FG aluminum coated silver
FGc = FG colored
RG = Roving glass
RGUD = RG uni-directional
RGR = RG random fibers
C = Carbon
CUD = C uni-directional

1.8 Properties of typical Tepex® materials

Fiber-plastic composites are characterized in particular by their excellent stiffness and very high strength coupled with very low density. These are the properties of an ideal lightweight construction material. The following table shows the key parameters of a number of standard Tepex® grades:

Figure 5: Material parameters of selected Tepex® materials

Tepex® material	Fiber	Polymer	Density (kg/dm^3)	Fiber volume content (% by vol.)	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Glass transition temperature (°C)	Crystallite melting point (°C)
STANDARD MATERIALS **Fast response time in material selection and manufacturing**										
Tepex® dynalite 101	E-glass Roving	PA 66	1,81	47	380	23	560	20	(–)	260
Tepex® dynalite 201	Carbon	PA 66	1,46	50	700	55	840	48	(–)	250
Tepex® dynalite 102	E-glass Roving	PA 6	1,80	47	390	23	580	20	(–)	220
Tepex® flowcore 102	E-glass Roving	PA6	1,80	47	L = 260 T = 220 (1)	L = 19 T = 14 (1)	L = 450 T = 300 (1)	L = 18 T = 14 (1)	(–)	220
Tepex® dynalite 104	E-glass Roving	PP	1,68	47	430	20	370	17	(–)	165
Tepex® dynalite 108	E-glass Filament	TPU	1,82	45	440	23	650	21	94	(–)
Tepex® dynalite 210fr	Carbon	PC(fr)	1,47	45	550	48	750	44	100	(–)

[1] L = longitudinal; T = transversal

2. PROCESSES FOR MANUFACTURING TEPEX® COMPONENTS

The process for manufacturing Tepex® components comprises the following steps:

1. Heating the composite sheet blank above the melt temperature* of the thermoplastic
2. Transporting the heated blank to the mold
3. Incorporating and positioning the heated blank in the mold
4. Forming using appropriate mold technology
5. If necessary, pressing or molding on a further thermoplastic component (combination technologies)
6. Cooling and removing from the mold

On account of this process sequence, the forming of Tepex® is also referred to as thermoforming. However, the following must be noted in this regard:

- Composite sheets are not formed in the rubber-elastic temperature range, unlike conventional thermoforming, but above the melt temperature*.
- Using appropriate mold technology and process control during forming and cooling, the Tepex® semi-finished product is subject to uniform pressure on all sides.

The heating and individual forming processes/techniques are outlined briefly below. Further information on the forming mechanisms for composite sheets and the resulting mold design can be found in Section 5.

2.1 Heating

Heating Tepex® reduces the viscosity of thermoplastic to a level that gives the individual fibers sufficient freedom of movement during the forming process. This is the only way to produce the draping mechanisms explained in Section 3 and to prevent wrinkling and cracks in the material.

*To be more precise: temperature range above the crystalllite melting point in the case of semi-crystalline plastics or above the glass transition temperature in the case of amorphous plastics.

The following conditions must be complied with:

- Tepex® must always be formed above the melt temperature of the thermoplastic used.
- The heating temperature should be high enough for the fibers to still have sufficient freedom of movement even after transportation to the mold when the mold closing movement occurs (keep transportation time and route as short as possible).
- The heating temperature and time should be selected so as to prevent oxidative damage.
- The heating process should be designed so that temperature distribution is completely uniform across the entire Tepex® surface.
- The temperature controls should be designed so as to prevent excessively high temperatures/temperature peaks.
- To ensure efficient process control, heating must not be allowed to determine the cycle time.

In principle, the following heating methods are available:

- Heating through radiation (infrared)
- Heating through convection (air flow)

Infrared radiation involves electromagnetic waves in the spectral range between visible light and microwave radiation. The semi-finished product blanks absorb the IR radiation and heat up as a result. Heat conduction also causes the inside of the composite to heat up. As thermoplastics and fibers have a high absorption capacity in the IR range, heat transfer is highly effective.

An equally widespread heating method in plastics technology is circulating air technology. Convection ovens with material feeding based on the paternoster principle have existed for a variety of applications.

2.2 Forming processes

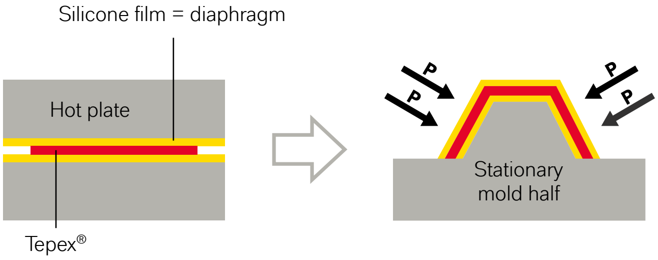
A wide range of different forming processes are available for forming Tepex®. Deciding which to use is based primarily on component complexity and the number of parts being produced. The individual processes are briefly described below.

2.2.1 Diaphragm process

Diaphragm forming is the oldest process for producing thin-walled components from continuously fiber-reinforced thermoplastics.

In diaphragm forming, the semi-finished product is placed between two highly elastic films, the entire structure is heated above the melt temperature* of the matrix using radiation or conduction and then transported to the forming station. The clamping bell is closed, with the diaphragms acting as seals. The heated laminate package is placed on the mold and then compressed air is applied to it. An additional vacuum can be applied to the mold to support the forming process.

Figure 6: Diagram of Tepex® diaphragm forming



The benefits of this process include low investment costs and the possibility of forming various material thicknesses with one mold. The process requires relatively long cycle times and is more suited to simple component geometries, even though minor undercuts are possible.

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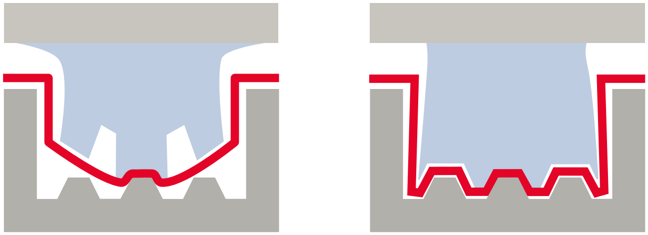
*To be more precise: temperature range above the crystalllite melting point in the case of semi-crystalline plastics or above the glass transition temperature in the case of amorphous plastics.

2.2.2 Forming with rubber stamps

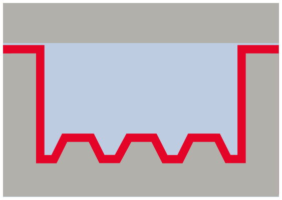
In this compression-molding process, the mold consists of a solid bottom mold half, corresponding to the outside of the component geometry, and a top mold half made of silicone. By closing the mold at low pressure, Tepex® is pressed into the part geometry.

Figure 7: Diagram of Tepex® forming using rubber stamps



1. Central bead formed

2. All beads formed



3. Completely formed

Thanks to its high elasticity, the silicone stamp enables sequential forming, which means the necessary, uniform pressure distribution can be ensured during forming (see also Section 3). An appropriate tool ventilation needs to be installed. Forming with rubber stamps is suitable for prototypes and smaller series due to the low investment costs and easy optimization of the stamps. However, the method has also demonstrated its suitability in large-scale series production for simpler geometries.

2.2.3 Forming with metal molds

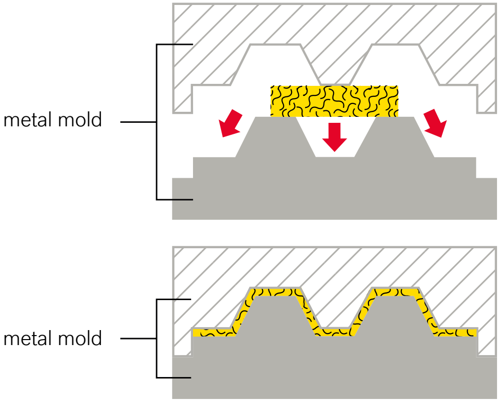
In most cases, Tepex® is formed using metal molds. Both mold halves are made of metal/steel and are temperature-controlled in relation to the polymer in question – i.e. matched metal-molding. In designing the mold, special attention should be paid to the cavity. Due to the special forming mechanism of composite sheets, basic factors need to be taken into account – see Section 3.

This forming technique in combination with appropriate automation enables very short cycle times and a highly reproducible process. Components manufactured using this process also exhibit only a very low tendency to warp. However, these benefits must be weighed up against higher investment and greater workload for the design. The method is thus particularly suitable for large series.

2.2.4 Flow-molding of Tepex® flowcore

As noted above, Tepex® flowcore is suitable for flow-molding due to its reinforcement with finite fiber lengths from approximately 30 to 50 mm. This therefore enables production of even more complex component geometries. Molding of ribs and functional elements is also possible. Flow-molding is a widely used method in plastics technology and is characterized by very high reproducibility and short cycle times.

Figure 8: Flow-molding of Tepex® flowcore



As with the established GMT and LFT thermoplastic flow-molding compounds, a precisely defined volume of Tepex® flowcore is first heated and then placed in an appropriate location in the mold. Forming the molded part/filling the mold is effected by closing the mold, which induces flow in the melt. Compression molds are generally used for this purpose.

2.3 Combination technologies

Combining Tepex® with plastics reinforced with short or long glass fibers with the same matrix system and their injection and flow-molding processes also offers the excellent option of using both lightweight materials and design, for example by injecting

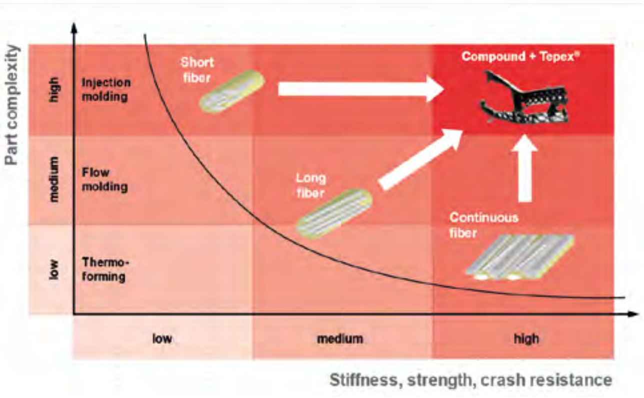
- reinforcing and stabilizing ribs
- force transmission elements
- functional elements
- contours at the edge of the component

An appropriate selection of materials and process control produce a component with a homogeneous bond between the two sections (see Figure 9).

This process innovation outlined below has its roots in the “SpriForm” research and development project funded by the German Federal Ministry of Education and Research (BMBF). Since then, this technology has been continuously optimized. Machine manufacturer Krauss-Maffei markets this combination technology under the “FiberForm” name, while machine manufacturer Engel uses the name “Organomelt.” A basic distinction is made between a two-step process (referred to in this brochure as insert-molding) and a one-step process (referred to here as hybrid-molding). The two methods offer the following benefits:

- Greater design flexibility
- Option of integrating further functions and thus reducing subsequent steps
- Combination of lightweight materials and design
- Short cycle times
- Reproducible and fully automated processes
- Available and manageable plant technology

Figure 9: Diagram of combination options for Tepex® with compounds



Regardless of the technology selected, good adhesion must be ensured between the two components by means of fusing. Adhesion depends primarily on the temperature of the composite sheet and the temperature of the melt at the time of injection. This results in the following process engineering conclusions, which may be confirmed through appropriate tests:

1. The higher the temperature of the composite sheet and the higher the temperature of the injection melt, the better the adhesion. As injection is performed at relatively high melt temperatures* and a contact temperature at the joint is produced, composite sheet temperatures below the melt temperature* are also usually sufficient.
2. The transfer time between heating the composite sheet and forming should be as short as possible to prevent cooling (as a general rule).
3. The injection speed has a significant influence on adhesion. The higher the speed selected, the greater the shear effect in the melt, and the lower the cooling effects, which has a positive impact on fusing. This effect is particularly noticeable in areas further away from the gate.
4. A high holding pressure also has a positive effect on adhesion.

*To be more precise: temperature range above the crystalllite melting point in the case of semi-crystalline plastics or above the glass transition temperature in the case of amorphous plastics.

2.3.1 Insert-molding (combination with injection-molding)

In the insert-molding process, forming of the composite sheet and overmolding/injection with plastics reinforced with short or long glass fibers take place in separate molds and machines. To achieve a homogeneous bond/fusing with the injected plastic melt, it is advisable to heat the preformed component (insert) once again before positioning it in the injection mold. This is the only way to achieve the required fusing of the two components.

2.3.2 Hybrid-molding (combination with injection-molding)

In hybrid-molding, by contrast, forming of the composite sheet and injection take place together in the injection-mold. The clamping unit of the injection-molding machine is used as a forming press in this process. The mold, which thus has various tasks to perform, needs to be specially designed for this process. Information on design can be found in Section 3. To produce molded parts in a single step, semi-finished composite sheets are provided as blanks that approximate the final contour. These blanks offer draping-compatible component production that can be calculated using a draping analysis (see also Section 6: "Design and calculation of components").

Figure 10: Insert-molding with Tepex®

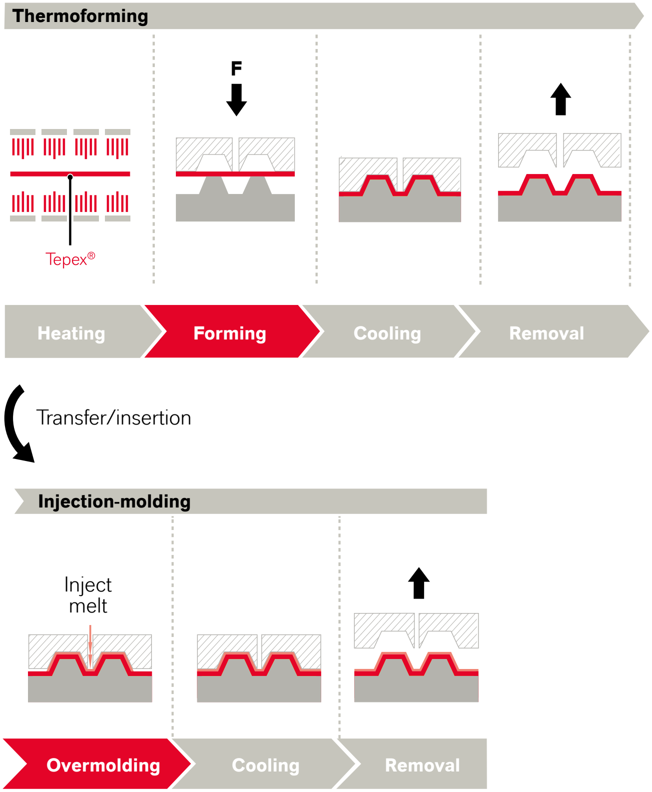
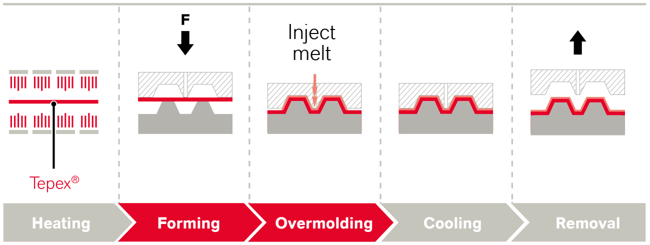


Figure 11: Hybrid-molding with Tepex®

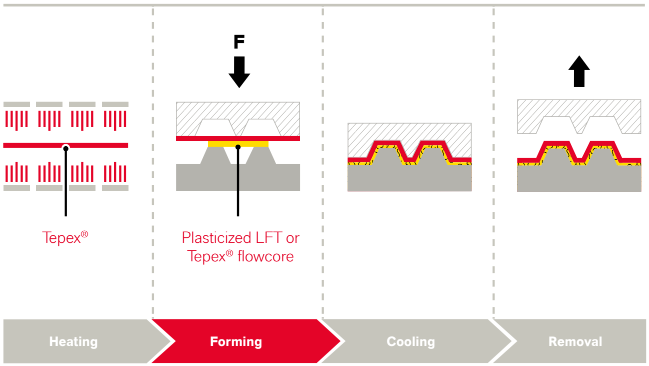


2.3.3 Compression-molding (combination with LFT flow-molding compounds)

LFT stands for long-fiber thermoplastics whose reinforcing fibers are at least 4 mm long. In this most popular direct method, the molding compound consisting of fibers, matrix and, where appropriate, additives is produced using extrusion technology immediately before the mold. The compound produced using this method is then processed using flow-molding with compression molds. The necessary flow of the melt is achieved by the clamping pressure of the appropriately designed mold.

Combining this method with preheated composite sheets enables easy production of large, extremely strong and distortion-free components in very short cycle times. The key characteristic of components produced in this way is their extremely high impact resistance.

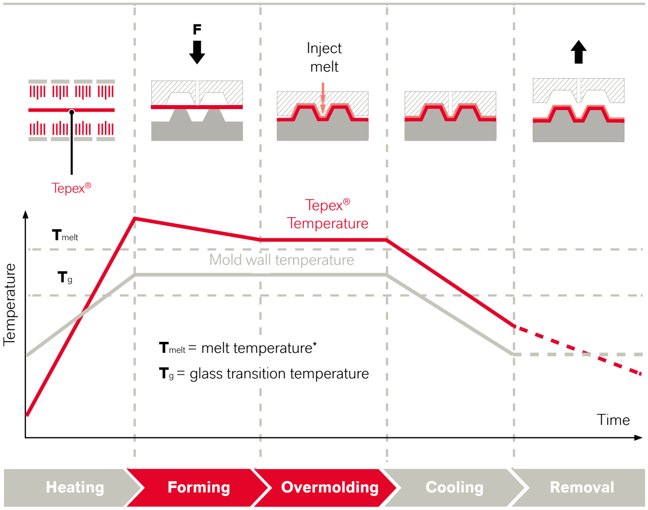
Figure 12: Tepex® hybrid-molding in combination with LFT or Tepex® flowcore



2.4 Variothermal process control

If necessary, the surface quality of Tepex® components can be further enhanced using variothermal process control. With variothermal temperature control of the mold, the mold walls are temporarily heated to a temperature between the glass transition temperature and melt temperature* of the plastic used. The mold is not cooled again till after forming of the molded part has been completed. This increase in the mold wall temperature delays solidification of the melt, with the result that the surface of components produced using this method can develop highly effectively. Figure 13 shows the process including the temperature cycles for Tepex® and the mold wall for hybrid-molding (combination of composite sheet forming and injection-molding, see start of this section).

Figure 13: Variothermal process control for hybrid-molding



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*To be more precise: temperature range above the crystalllite melting point in the case of semi-crystalline plastics or above the glass transition temperature in the case of amorphous plastics.

3. MOLD DESIGN AND HANDLING SYSTEM

There is now a wealth of experience about how to optimally structure molds for processing Tepex® and how the handling components can be designed accordingly. With its HiAnt® customer service, LANXESS supports customers' projects in all matters involving mold design. Numerous machine and mold manufacturers now also specialize in processing composite sheets. A fundamental understanding of the forming mechanisms of plastics reinforced with continuous fibers is key to designing and handling Tepex®.

3.1 Draping of Tepex®

The special forming behavior of Tepex® has a major influence on mold design. Forming, also known as draping, only rarely uses flow processes as in conventional plastics processing methods, and instead is based largely on forming the semi-finished textile product (draping). There are essentially two different draping/forming mechanisms, which are shown in Figure 14 (fiber elongation, fiber stretching and fiber slippage are disregarded here):

- Angle changes/fabric shear strain of the semi-finished textile product, also referred to as the trellis-effect
- Movements of individual layers relative to each other, also known as interply shear (in multilayer laminate structures)

These two mechanisms, either individually or in combination, enable very high degrees of forming. In areas of the component with pronounced three-dimensional deformation, the fiber orientation changes to a greater or lesser extent relative to the original state. This results initially in an unavoidable thickening of the material, which needs to be taken into account in mold design (see Section 3.3 "Designing the mold cavity"). If draping is increased further, blocking of the textile may occur, resulting in unwanted wrinkling. A draping simulation provides information on such critical degrees of forming so that appropriate countermeasures can be taken.

Figure 15: Results of a draping simulation (shear angle as a measure of fabric shear strain)

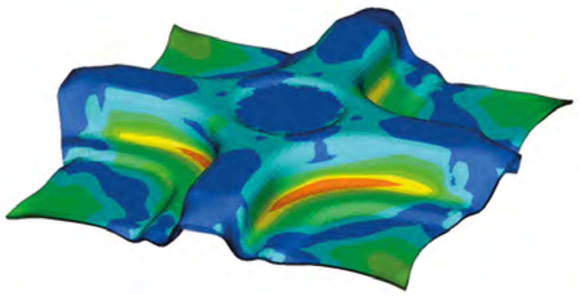
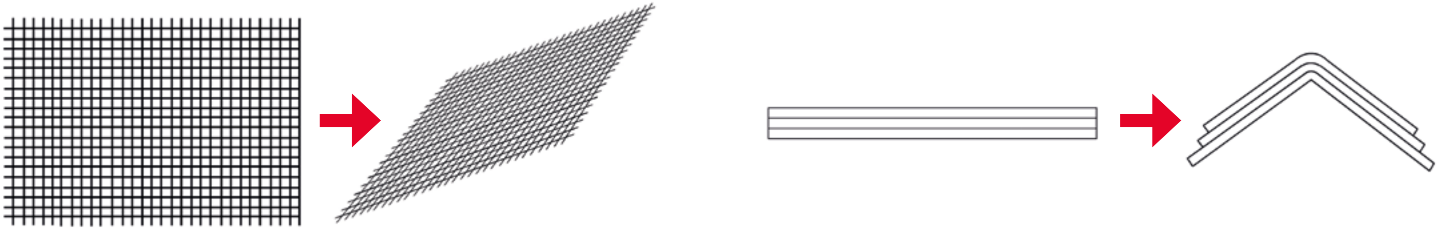


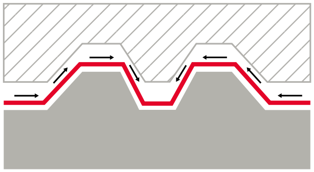
Figure 14: Tepex® forming mechanisms; left: trellis-effect; right: movement of individual layers



3.2 Design information on the specific forming behavior of Tepex®

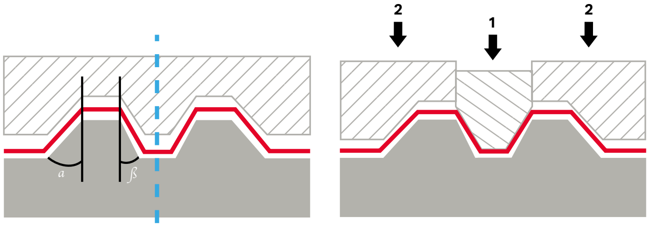
As well as the forming mechanisms described above, knowledge of the special kinematics of forming Tepex® is particularly important for mold design. To ensure reproducible, consistent forming of the component, the heated composite must be able to slide freely from the outside to the middle of the mold during forming.

Figure 16: Sliding of Tepex® during the mold closing movement



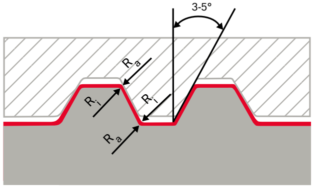
In more complex geometries, an unfavorable mold design may lead to stresses occurring between neighboring areas of the component, which may result in the material jamming or even tearing. Here, too, a draping analysis covers such areas and provides valuable information for designing the mold. Several design solutions are available to solve this problem. The angles of the flanks should increase from the center of the cavity toward the edge of the mold, as can be seen in the illustration below. Slides or moving stamps can also be used to ensure staggered entry of the material into the mold and thus sequential forming. If necessary, checks should be made to see whether component areas with very small angles can be formed using active elements such as slides.

Figure 17: Solutions to prevent stress during forming (left: adjusting the angles, right: integrating a slide)



To ensure that Tepex® components can be shaped effectively as shown above but also demolded quickly and reliably, opening angles/drafts of ≥ 5 degrees are recommended for vertical areas of the mold independently of the material thickness. Contours with drafts of ≥ 2 degrees can also be used to a limited extent.

Figure 18: Design of radii



If possible, the inner and outer radii of angular contours should be designed according to the following rules – partly to ensure that the fibers are not damaged during forming due to excessively sharp mold edges:

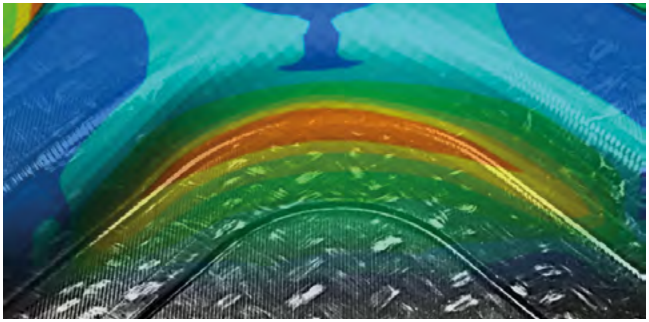
- Inner radius $R_i \geq$ Tepex® wall thickness, but at least R_1 (1 mm)
- Outer radius $R_a \geq$ inner radius R_i + Tepex® wall thickness

3.3 Designing the mold cavity

Tepex® is supplied fully impregnated and consolidated. The individual fibers of the semi-finished textile product are thus enclosed by the thermoplastic matrix, and the laminate contains virtually no air inclusions. When heated above the melt temperature* of the thermoplastic matrix, the thickness of Tepex® increases by up to 20 percent. This is largely explained by the increase in the volume of the plastic and the release of internal stresses in the semi-finished textile product by heating. During forming, the semi-finished product must therefore be pressed back to the nominal wall thickness so that a compact, smooth surface without imperfections is created and ideal properties are achieved in the component.

As a basic principle, it is advisable to design the mold cavity area where Tepex® is formed in line with the required wall thickness of the component. However, special attention should be paid to areas with a high degree of draping (high shear angle). As briefly explained in the previous sections, thickening occurs here due to a buildup of material. This often cannot be pressed back to the required dimension, despite elevated molding pressures, which means that adjacent areas cannot be subjected fully to pressure because the mold is blocked and thus cannot be formed correctly (see Figure 19). The cavity in these areas then needs to be correspondingly thicker to ensure uniform pressure distribution across the entire component.

Figure 19: Shear angle distribution projected onto an actual component; red area indicates a local thickening



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*To be more precise: temperature range above the crystalllite melting point in the case of semi-crystalline plastics or above the glass transition temperature in the case of amorphous plastics.

In principle, a uniform and smoothly formed surface on the manufactured component may be viewed as an indicator of good mold design, as this is a sign of uniform pressure transfer from mold to component surface. However, in addition to a well designed mold, process control also has a significant influence on surface quality:

- Temperature of the Tepex® insert
- Surface temperature of the mold (see also “Variothermal process control”)
- Molding pressure
- Surface quality/properties of the mold

In summary, it may be noted that the precision of the cavity gap is key to component design.

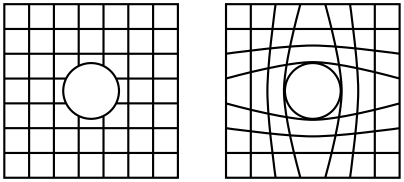
3.4 Integrating holes

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

1. Holes are made when producing the Tepex® insert by cutting or drilling
2. Holes are created during forming by pushing back the fibers with a pin

The second option appears advantageous particularly for high stresses on the faces of holes, as it is possible to divert the flow of forces around the holes. Figure 20 illustrates this situation.

Figure 20: Making holes – left, by cutting or drilling; right, by forming and pushing back the fibers in the mold



3.5 Design information on overmolding Tepex®

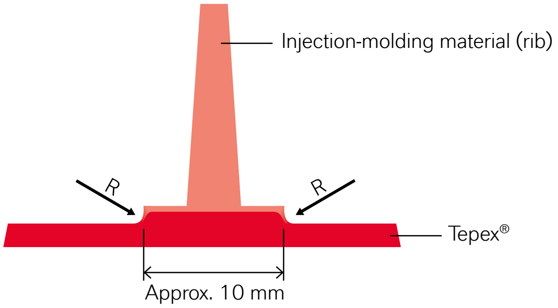
As already explained in Section 2.3, a homogeneous bond can be achieved by injecting a plastic reinforced with short or long fibers and the same matrix as that of Tepex®. This enables the design of complex components with high strength and stiffness. Figure 21 shows a section of such a component. A typical rib structure can be seen that also stiffens and stabilizes the component. Typical edge overmolding is also visible.

Figure 21: Example of rib structure and edge overmolding

3.5.1 Rib design

Two factors must be taken into account in designing ribs for overmolding Tepex®. Firstly, the rib base should cover a large area, as in the diagram below. Good experience has been gained using a width of approximately 10 mm, which achieves a very good bond between the rib and composite sheet, provided there is optimum process control (see Section 2.3).

Figure 22: Diagram of rib design

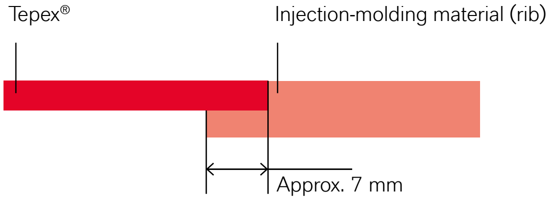


Sharp edges in the area of mounting the rib base onto the composite sheet also need to be avoided. Rounded corners prevent damage to the fibers when mounting the mold.

3.5.2 Designing the edges

In designing force-transmission and functional elements and the edges of a component, a combination of frontal and overlapping molding on is recommended, as shown in the following diagram.

Figure 22: Diagram of edge design



An optimum bond can be produced in this way, in combination with appropriate process control.

3.5.3 Patching / overlapping of Tepex®

Using tailored blank technology as a basis, different composite sheets can also be combined to adapt the component to local component stresses using different sheet thicknesses. These sheets are preferably first heated separately and only then combined and formed in or before the mold. The similar matrix results into a positive bonding.

3.6 General design information on handling Tepex®

The handling of the Tepex® insert plays an important role in ensuring high reproducibility of the manufacturing process and the component properties. It leaves the heating station in a hot and plasticized state and is thus limp. This must be taken into account when transporting the material to the mold, closing the mold and during the actual forming, as well as when overmolding and back-injecting. The handling system has to perform the following functions:

- Secure gripping during and after heating
- Preventing local cooling by grippers
- Fast transportation to the mold by the shortest possible route
- Reproducible transfer to the mold in the correct position

In the mold, it then needs to be ensured that

- the blank is mounted in the correct position without heat loss, and
- the blank is approved for forming during the mold closing movement

The following gripper methods for handling are recommended for transportation between the heating station and mold:

- Needle grippers incl. stripper bushes (are stuck into the composite sheet)
- Clamping pins, point grippers (double-sided clamping)
- Vacuum suction device
- Pins (they hold the composite sheet in previously made holes)

For incorporation into the mold, use can be made of

- needles to fix the blank
- swiveling retaining fingers
- clamping pins in both mold halves, which are used to insert the blank centrally between the two mold halves
- Vacuum suction device

To prevent cooling of Tepex® in the mold, early contact with the relatively cold mold walls should be avoided in designing the transfer system. These mounts also need to be designed in such a way that when the mold is closed, the Tepex® is kept in a reproducible state and in the correct position during forming without impairing the draping.

4. JOINING TECHNIQUES FOR TEPEX®

Tepex® components are often part of complex assemblies that, in extreme cases, combine different materials, including steel, light metals such as aluminum and magnesium, plastics reinforced with short or long glass fibers, or carbon-fiber composite materials. To manufacture such assemblies quickly, automatically, to a high level of quality and at low cost, Tepex® may need to be joined with itself or with other materials. To do this, processes may be used that are long established for thermoplastic components in industrial series production.

The various joining processes differ according to the physical principle of action:

- Homogeneous bonds (welding, adhesion)
- Non-positive processes (fastening with screws, pressing, riveting)
- Positive processes (catches, locks, brackets)

There is also a differentiation between separable (screws, pins, wedges) and inseparable connections (adhesion, welding, riveting). While welding can only be used for thermoplastic semi-finished products, by using adhesion and mechanical joining it is possible to connect various material combinations, even plastics, to completely different materials such as metal.

A concrete configuration for a joining process should always be produced on a component- and application-specific basis. In this regard, please refer to adhesive manufacturers, manufacturers of connecting elements (screws, rivets etc.), machine manufacturers (welding) and engineering service providers, who can reliably assess and design such processes using their expertise and experience.

4.1 Bonding

Component bonding is an established homogeneous joining technology that also makes it possible to combine incompatible materials with each other. A wide range of adhesive systems are available on the market that are in some cases tailored to specific material combinations.

Users can employ established systems to select an appropriate adhesive system for Tepex®. Knowledge of the composite matrix and bonding partner is generally sufficient – adhesive systems specially tailored to Tepex® are not necessarily needed.

Systems made of two-component epoxy adhesives, two-component acrylate adhesives and two-component polyurethane adhesives have already been series-tested as solvent-free, low-shrinkage adhesives.

The components must be designed in a way that is conducive to adhesion. The following types of load may occur with adhesive bonding:

- Tensile stress – should be avoided, as the tensile strength of adhesives is often less than the strength of the adherends.
- Tensile shear stress – overlapping adhesive bonds enable the formation of larger joining surfaces and thus the transfer of greater forces under relatively low shear stress in the bonding joint. The ideal scenario.
- Peeling – peel forces trigger stresses perpendicular to the bonding joint. Unclear stress conditions, estimation of protection against damage almost impossible. If peel stresses are unavoidable, they should be reduced through appropriate measures.
- Bending and gap stresses – should also be avoided, as they may lead to high stress peaks.

Cleaning, roughening the surfaces and/or activating or using special primers increases adhesive strength.

Tepex® can also be joined with commercial structural adhesives that cure at cathodic dip coating (CDC) temperatures. This increases the possible applications for the composite material in the manufacture of lightweight bodywork parts, as no additional energy is needed for heating and curing the adhesive.

4.2 Joining using injection-molding

As already described in Section 2.3, joining using injection-molding is an efficient, versatile joining process for thermoplastic composites such as Tepex® that has become established in series production. If the injection-molding material and composite matrix are polymer-chemically compatible, the result is a homogeneous bond with excellent adhesion. This technique can even be used to join several Tepex® blanks with metal components in a single process step to create complex assemblies. While the connection between the thermoplastic composite and injection-molding material is generally a homogeneous bond, the connection with incompatible bonding partners such as metals is made either by a positive connection mechanism (injecting breakthroughs or anchoring the polymer to surface features) or by using processing aids. An appropriate bonding agent that enables a secondary adhesive bond between Tepex® and metal can thus be applied to sheet metal.

4.3 Mechanical joining processes

Self-tapping screws that have thread flanks with an angle of between 20 and 30 degrees should be used to fasten Tepex® components. Given that the fiber structures generally need to be penetrated by introducing joining elements, these elements should either not be introduced into the primary load paths of the component, or alternatively the fibers can be displaced in the plasticized semi-finished product so that they traverse around the hole into which the joining element is later introduced without being damaged (see Section 3.4 Integrating holes). Alternatively, load-introducing geometries such as screw domes can be molded in place during component production.

In general, force should be transmitted less via the face of the hole and more at the semi-finished product or component level as appropriate. This can be done by using large joining element heads and appropriate pre-tension.

4.4 Welding

As Tepex® is based on a thermoplastic matrix, appropriate welding processes lend themselves to this purpose. In welding, use is made primarily of physical adhesion mechanisms so as to generate a connection between two or more bonding partners. This involves the bonding partners being transformed into a melted state at least on a local basis and then brought into contact with each other under pressure and cooled again under the joining pressure. During the joining phase, the adhesion processes are activated and generally remain reversible when cooled.

A variety of processes are available that have already long been used in conventional thermoplastic processing. The processes are suitable for series production and have been thoroughly tested with thermoplastic components. Among other aspects, they differ according to weld seam strength, cycle times and suitability for small or large batch sizes.

The welding processes can be classified according to the application of heat. The following types are distinguished:

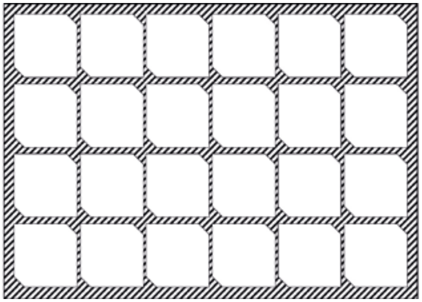
- Heating through heat conduction
- Heating through radiation
- Heating through movement
- Heating through convection

A very good overview of the individual welding processes and their suitability for thermoplastic fiber composites is given in “Handbuch Verbundwerkstoffe” (Hanser Verlag) by Neitzel, Mitschang and Breuer.

5. RECYCLING TEPEX®

When cutting out application-specific blanks, a certain level of waste is produced, as can be seen in the example in Figure 24. To minimize this waste, the relevant geometries are nested in the Tepex® semi-finished product to obtain an optimum yield, taking into account the necessary fiber orientation. During the development phase of Tepex® components, everyone involved should therefore pay great attention to optimizing the blank geometry with regard to reducing material loss. Even the smallest adjustments can increase the yield considerably.

Figure 24: Example of waste after cutting the component geometry to size



In the case of curved geometries that are very difficult to nest, the possibility of the component also being designed using a number of Tepex® blanks that are then combined in the mold should be examined. This often results in material being used much more effectively.

Unavoidable waste can be sent for recycling. As Tepex® is a fiber-reinforced thermoplastic, the following recycling methods can be used:

- Material recycling using mechanical processing
- Feedstock/chemical recycling, i.e. separation into individual components using hydrogenation, hydrolysis and pyrolysis
- Energy recycling to recover the energy contained in the plastic

Material recycling offers the greatest economic benefits in recycling residual material and waste. In this process, the Tepex® waste is first ground to a defined particle size using cutting mills or multi-shaft crushers. The resulting granulated material can then be sent directly to a typical plastics processing operation. Due to the granulated material's low bulk density, forced dispensing should be used in order to prevent bridging in the hopper.

By adding non-reinforced new material, the recycled material's fiber content can be controlled precisely to produce regranulate. With PP-based Tepex®, diluting the granulated material to a fiber mass content of 30 percent is recommended. Other Tepex® grades can also be processed undiluted. The mechanical properties (strength, stiffness, toughness) of the recycled material are comparable with standard plastics reinforced with short fibers with appropriate fiber content.

Figure 25: Value chain: Tepex® ➡ granulated material ➡ regranulate ➡ component made from recycled material

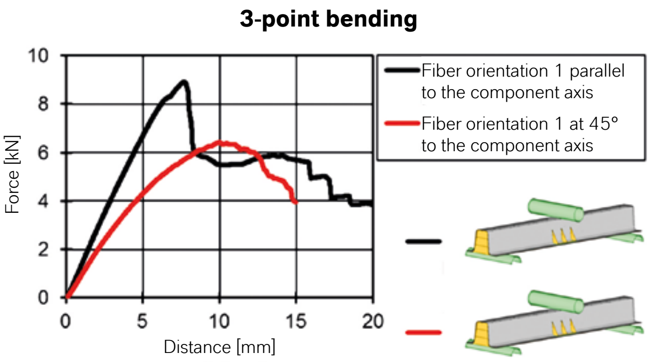
6. DESIGN AND CALCULATION OF TEPEX® COMPONENTS

Tepex® offers designers tremendous freedom in the load-optimized design of heavy-duty yet lightweight components. The characteristics of these components depend on the thermoplastic for the matrix, the type of continuous fiber (glass, carbon) and the type of fabric or inlay used (unidirectional, bidirectional, multiaxial).

One of the key factors in the engineering process is the directional dependency (anisotropy) of the mechanical properties that results from reinforcement with continuous fibers. Unidirectional continuous fibers embedded in a thermoplastic matrix exhibit the properties of the fibrous material in the direction of the fibers (one direction), whereas perpendicular to the fibers (two and three directions), they tend to exhibit the properties of the matrix.

With Tepex® components, the length of the fibers correlates with that of the components. Wherever possible, designers should therefore orient the fibers in the direction of the applied loads so that the flow of forces between points of force application takes place through the continuous fibers. However, a more complex state of stress in the component (e.g. combined shear and tensile stress/compressive stress in the curved profile) may also require a combination of various fiber orientations. A symmetrical layer structure is beneficial in ensuring low-distortion component design. The forces should also be absorbed over as large an area as possible to avoid excessive stress and notch effects as far as possible and to always apply a load to multiple fiber rovings.

Figure 26: The diagram shows the influence of fiber orientation on component behavior



6.1 FEM calculations – conditions and special characteristics

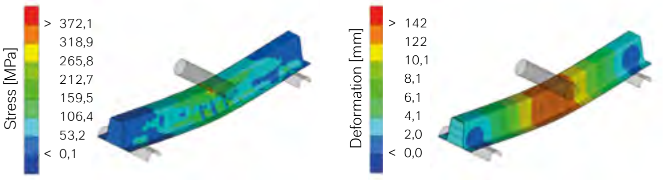
Computer-aided engineering (CAE) of Tepex® components is essential to achieve short development times, cost-effective production processes and component design that is optimized for the load cases. In this process, the design relates specifically to both the production process and the mechanical behavior of the component and the interaction between production and component properties.

As noted in the introduction, the anisotropy – i.e. directional dependency – is the most important property of the semi-finished product in the design process. The morphology of the reinforcing fabric gives rise to a tension-compression asymmetry, a dependency on the position in terms of the through plane (layer structure) and, for the manufacturing process, the drapability. The matrix properties give rise to the temperature and, in some cases, moisture content dependency, as well as – depending on the type of load – time-dependent creep. The layer structure also produces relatively large differences between tensile and flexural properties.

Both the manufacturing process and component behavior can be characterized highly effectively using standard FE methods and calculation programs (solvers), with precision and forecast quality depending on the model-based approach used, the scope of the underlying measuring data and the specific aspects to be calculated.

In order to sufficiently predict the manufacturing process, the resulting fiber orientation and the component properties through to fracture behavior, LANXESS has developed tools based on the FE solver ABAQUS that characterize the properties and influences referred to and can thus be used directly in the development process for Tepex® components. These FE tools use material data that are calculated using direction-dependent tensile tests, sometimes with a high expansion rate, and various shear and flexural tests.

Figure 27: Stress distribution and deformation in three-point flexural testing with the HiAnt® beam



6.2 Draping simulation

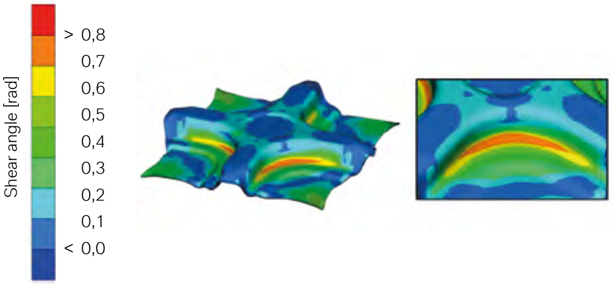
Forming and draping simulations serve two aims that are independent of each other:

- Determining the distribution of local fiber orientations and shear angles in the fabric. These are needed in the mechanical calculation to take into account the anisotropic material behavior. This calculation is often needed early in the project in the concept phase to mechanically analyze various concept proposals at this stage. Simulation of fiber orientations must therefore be performed quickly and easily and require as little information as possible about the mold that is not yet available at this time. To do this, LANXESS uses an FE-based calculation method that determines the relevant blank and the distribution of orientations for a given Tepex® geometry very quickly (approximately one hour). The process is not exact, but is generally sufficiently precise (one-step draping).
- Complete representation of the draping process, taking into account blank geometry, mold geometry, slides, retaining needles, handling system etc. The task here is to map the process, identify any errors at an early stage, develop suggestions for improvement and assess process reliability. Calculation of fiber orientation is somewhat in the background in this case. A complete draping study is ideally carried out if

the component geometry is essentially fixed and mold data are already available (at least for mold surfaces), yet some flexibility still exists.

The simulation model developed by LANXESS for the draping of Tepex® components is based on the FE solver ABAQUS. It takes into account the fact that thermoplastic fabric-based composites do not allow plastic thermoforming but instead are added to the component's three-dimensional geometry as a result of fabric shear strain from the flat mold (trellis-effect). If the shear effect which is necessary for forming is so large that the fibers lock together, the material switches to the normal direction and wrinkles are produced. This effect can also be reproduced in the calculation model.

Figure 28: Shear angle distribution in a mock-up component

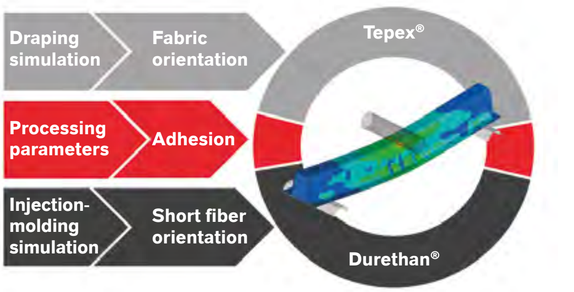


6.3 Integrative simulation

The composite material model for Tepex® developed by LANXESS, combined with the fiber orientations determined for the component geometry in the one-step draping process, enables highly effective precalculation of the component's stiffness, strength, crash properties and vibration characteristics. The tools can be used both for pure Tepex® components and those produced using insert-molding, hybrid-molding or flow-molding. Designers can thus react to a weakness in a component at the computer stage – for example by using greater wall thicknesses or reinforcing ribs

Both tools have proven their suitability and precision in the development of numerous prototype and series components – such as in the case of a front end upper belt, brake pedal, airbag housing, seat shell and infotainment bracket (load-bearing structure of the sound system in a vehicle).

Figure 29: The illustration shows the key influences on integrative simulation of Tepex® hybrid components



6.4 Simulation of cooling behavior

LANXESS has supplemented the forming simulation and the new material model for Tepex® with a modeling approach that also supports simulation of thermal processes in heated Tepex® during forming. This simulation model essentially makes it possible to examine uneven cooling under slides, for example, and its reverse effect on drapability, which results from the temperature-dependent material behavior.

As this simulation process requires precise information on the heating process and all the thermal conditions and is much more complex overall than the isothermal approach, it is normally only used for analyzing very specific questions and problems.

6.5 Designing Tepex® components independently

LANXESS uses integrative simulation in joint development projects so as to provide customers with support in developing components. Yet it is also important to give our customers tools they can use to design new applications in Tepex® as part of their own CAE workflow. To this end

- a material model has been validated for the commercial program Digimat from e-Xstream and populated with data. Our customers can use this program in combination with a number of calculation programs. An appropriate program license is needed to use the Digimat solution.

- a standard material model for LS-Dyna (MAT 58) has been identified with which many different design problems can be dealt with effectively.
- linear material datasets that enable a simple stiffness analysis regardless of the code used have been provided for most Tepex® grades.

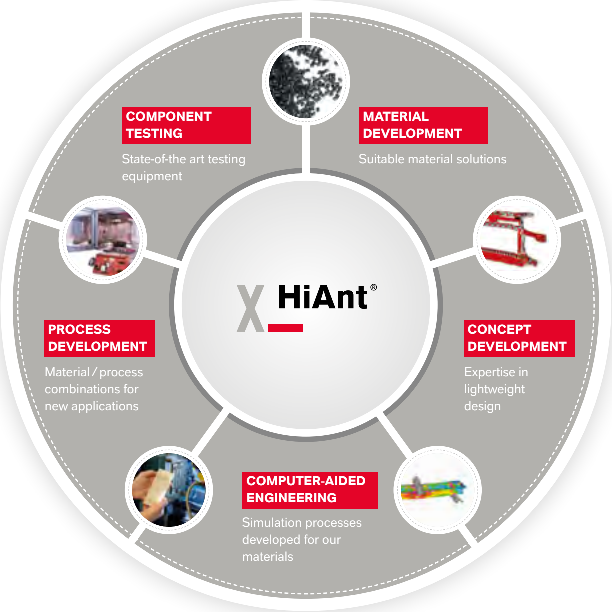
An expanding reserve of material parameters is available for all methods. All cases require the orientation distribution, which LANXESS can calculate by using the one-step draping process, for example, and make available for a specified calculation model, to be saved.

7. HIANT® – SERVICE ALONG THE ENTIRE DEVELOPMENT CHAIN

The HiAnt® brand represents the complete know-how that LANXESS possesses when it comes to materials, composite technologies, simulation methods, component testing, processing and manufacturing. We introduce this expertise to our partnerships with our customers.

HiAnt® services for Tepex® include:

- Assistance in selecting materials, taking account of component requirements
- Provision of customized polymer grades for insert-molding, hybrid-molding and flow-molding
- Materials testing to determine material parameters for mechanical structural analysis and component design
- Simulation of forming (draping) of Tepex®
- Integrative simulation for the load-optimized design of continuous-fiber composite components
- Reproduction of customers' manufacturing processes in our fully automated, production-quality demo cells to determine process parameters and for quality control and improvement
- Component testing such as mechanical component and climate change tests



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