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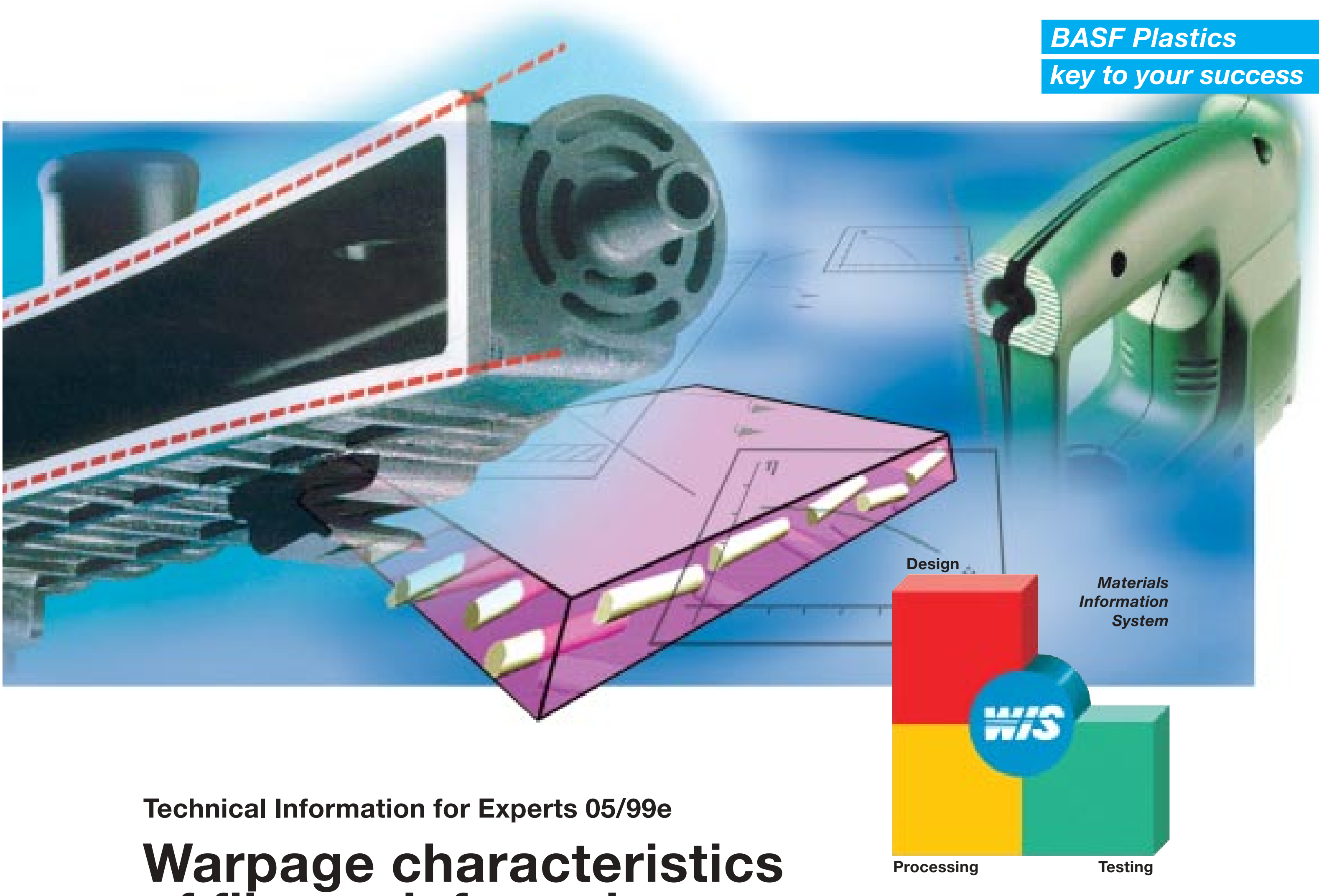


Technical Information for Experts 05/99e

# Warpage characteristics of fiber-reinforced injection-molded parts

■ There are marked differences in the shrinkage characteristics of unreinforced and glass-fiber reinforced thermoplastics. ■ The design rules applicable to unreinforced plastic parts for minimizing warpage have only limited validity for glass-fiber reinforcement. The dominant determining factor in this case is the orientation of the fibers. ■ In order to be in a position to take any possible warpage into consideration as early as the design phase or to optimize the warpage behavior of prototype parts, the causes and mechanisms of fiber orientation together with their effects on shrinkage behavior must be known. This understanding allows the derivation of design rules and measures for the minimization of warpage. ■

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If a molding deviates from its desired shape, e.g. it has arched surfaces or edges or exhibits changed angles, this is referred to as component warpage. This warpage is brought about by local differences in shrinkage caused, for example, by anisotropies of the material or inhomogeneities in the temperature distribution. **Fig. 1** explains the relationship between inhomogeneous shrinkage and changes in shape.

The usual design rules for minimizing molding warpage and the common counter-measures when running in a new mold relate primarily to unreinforced materials. Thus sometimes considerable design and mold-making effort is expended in order to avoid the "mortal sin" in the forming of plastics: thick sections. Efforts are made by means of multipoint gating to keep the pressure gradient in the molding to a minimum. Furthermore, the substantial effect of mold cooling on warpage is known but less consideration is given to the effect of molecular orientation which is only of importance in very flexible, especially flat, parts.

In the case of reinforced molded parts on the other hand there is one dominant factor: fiber orientation. Variations in pressure and temperature and even crystallization are of only secondary importance.

Accordingly, the known design rules for minimizing warpage have only limited validity while at the same time quite different considerations come to the fore.

In what follows the mechanism of fiber orientation during the filling and holding pressure phases and its effects on the molding are presented. From an understanding of the processes in the material a series of rules can be derived for the general avoidance of warpage.

## Distribution of shrinkage

The mechanical properties of glass and thermoplastics differ by orders of magnitude. A glass fiber is approximately 40 times more rigid than the plastic surrounding it, while its thermal expansion is only about 1/30th. The composite characteristics of the molding compound are built up from the characteristics of the components in accordance with the fiber content. The fibers exert their effects primarily in the direction of the fibers while in the direction transverse to this the properties of the plastic predominate **(Fig. 2)**.

Due to the fiber orientation caused by processing the properties of the processed material are no longer homogeneous. On the contrary, there are different local distributions of rigidity and shrinkage which are dependent on orientation across the surface and wall thickness of the molding. This anisotropic behavior of the material becomes very evident even at low fiber contents (10 wt.%).

To begin with some clarification of terms: During cooling in the mold a plastic contracts or shrinks. For the mold-maker the shrinkage is the change in length of the entire molding. From the considerations described above, however, it becomes clear that the shrinkage of the molding is by no means uniform and that this overall change in length is the sum of all locally different shrinkages. Accordingly, the term shrinkage will always be used in what follows as a local dimensional change in a locally bounded region of the component.

## Melt flow and fiber orientation

When a plastic melt flows through the gate into the mold cavity it starts to spread out radially. As this causes the flow front to become larger the melt undergoes elastic extension at right angles to the direction of spreading. The alignment of the fibers as a result of this extensional flow is so marked that it is largely unimportant what orientation the fibers had previously (in the runner/gate).

While the melt is filling the cavity a flow profile simultaneously sets in across the thickness of the molding. The flow rate is greatest at the center while at the edge it falls to zero due to adhesion to the cold mold wall. As a result the melt is exposed to a shearing force which in the final analysis is responsible for the flow resistance and hence for the filling pressure.

***Figure 1:*** *Homogeneous and inhomogeneous shrinkage*

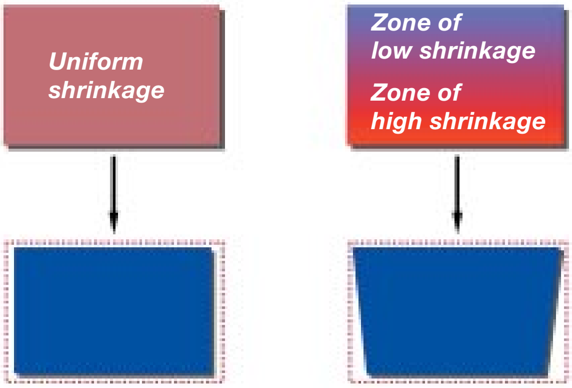
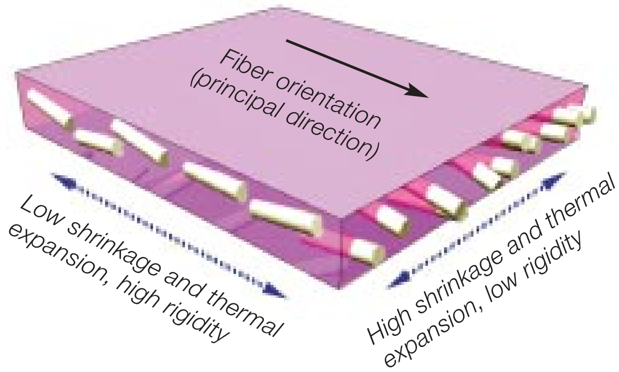



***Figure 2:*** *Cutout section of a component (containing glass fibers)*



The shearing of the material is, however, not uniform over the wall thickness. Rather, there is a pronounced shear layer close to the wall while the melt in the center flows more like a plug or block and is scarcely subjected to shear. A melt particle which flows forward very quickly in the central layer will finally be steered on the jet-like flow front into the vicinity of the wall where it is then subject to shear.

The fibers are oriented by the two mechanisms of shear **(Fig. 3)** and extension **(Fig. 4)**.

In the cavity both mechanisms are superimposed on one another **(Fig. 5, left)**. A volume of melt which has just advanced past the gate into the cavity first of all receives a very marked transverse orientation. It then flows with the plug flow in the center of the channel in the direction of the melt front and undergoes practically no reorientation in doing so, i.e. the fibers are still transverse to the direction of flow. At the melt front the volume of melt is diverted towards the wall and in doing so it becomes subject to shear flow which aligns the fibers in the direction of flow. The two mechanisms, therefore, produce three layers across the wall thickness of the molding each with main fiber orientations at 90° to one another. This can be clearly seen in photomicrographs of polished sections.

The mechanical properties of the molding depend now on the thickness of these layers and the degree of orientation in each one. At points where the peripheral layers predominate the molding is more rigid in the direction of flow than in the direction transverse to this. In addition the fibers impede shrinkage in the flow direction here. On account of their particular descriptiveness the main orientations averaged over the wall thickness of the molding are presented below.

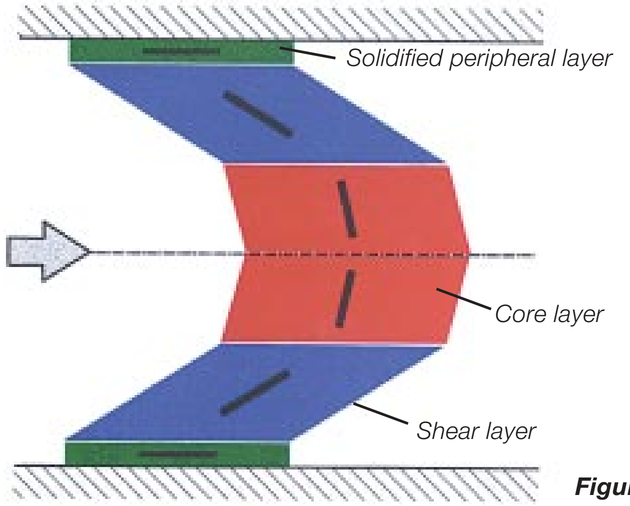



***Figure 3:*** *Shear flow*

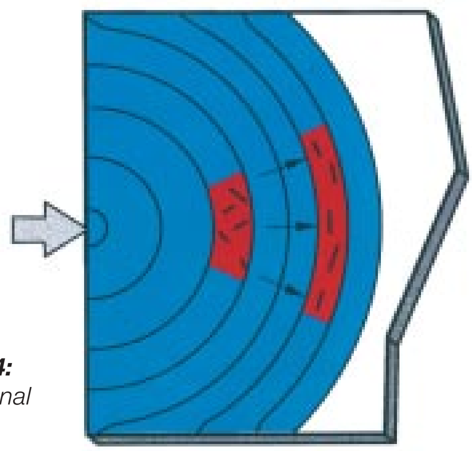



***Figure 4:*** *Extensional flow*

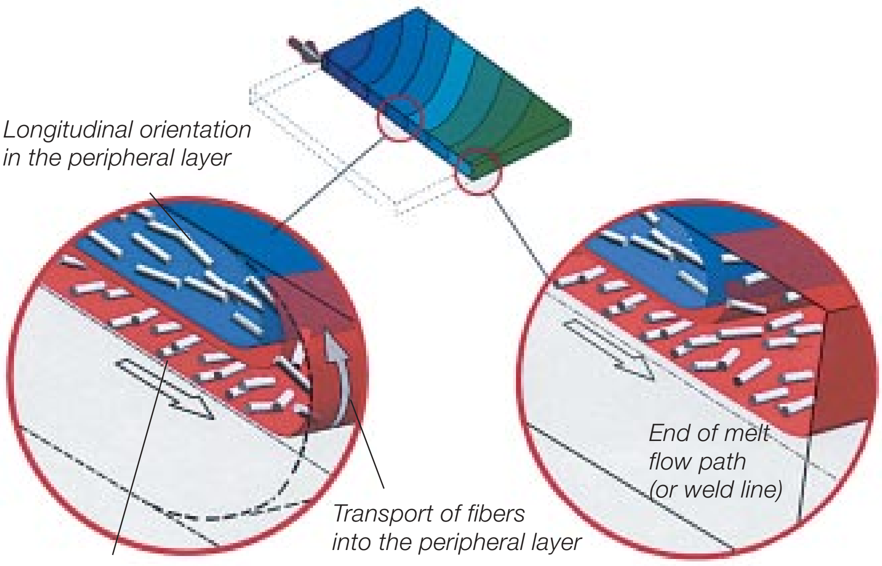



***Figure 5:*** *Fiber orientation in a sheet*

Although the thicknesses of the layers are affected by the geometry, the overall wall thickness, cooling and the way the process was conducted the most important determining factor is the viscosity of the plastic in question. A polymer having marked intrinsic viscosity (e.g. polypropylene, PP) has a dominant core layer. If on the other hand there is low intrinsic viscosity (e.g. polyamide, PA) the situation is reversed and the great bulk of the fibers lie in the direction of flow **(Fig. 6)**.

The holding pressure, which is decisive in unfilled materials for maintenance of shape and warpage, does not play such an important role in fiber-reinforced thermoplastics since although the local shrinkage behavior also depends on pressure and temperature it depends primarily on fiber orientation. Changes in wall thickness often employed in practice in unreinforced materials for the selective control of shrinkage have only very slight effects here. However, in certain circumstances considerable melt flow can still also occur in the holding pressure phase and hence give rise to changes in orientation.

Even the temperature control of the mold has only a relatively low effect. Warpage caused by orientation can be compensated to only a limited degree even by gross differences in temperature.

## Fiber orientation as the cause of warpage

Fiber orientation or layer formation alone does not necessarily trigger warpage. Only when the orientation (angle of orientation and degree of orientation) changes from point to point do local differences in shrinkage and hence internal stresses and possibly deformations occur. The causes for such different orientations may be:

- diversions of flow during the filling phase
- transverse orientations at the end of the melt flow path **(Fig. 5, right)**
- weld lines
- gates.

The causes, effects and remedies are treated at length below. In doing so the focus is on engineering plastics (PA and PBT), that is those having a dominant peripheral layer.

## Diversions of flow during the filling phase

The aim must be to obtain a uniform fiber alignment throughout the molding so that in view of the great differences in shrinkage in the longitudinal and transverse directions of the fibers the shrinkage behavior obtained is as uniform as possible. Only the orientation in the completely filled cavity is important not that when the cavity is partly filled. Both the flow history as well as the movements of the melt which last occur in the holding pressure phase have an important effect on the final orientation.

**Fig. 7** shows an illustrative example of this. If a rectangular plate is side-fed with disregard for the symmetry of the part, when the mold is 90 % full there is at first still a symmetrical pattern of orientation. However, in the final phase of filling when the melt still only has to fill the right-hand region of the cavity the fiber orientation or the degree of orientation is changed once again in the regions already filled.

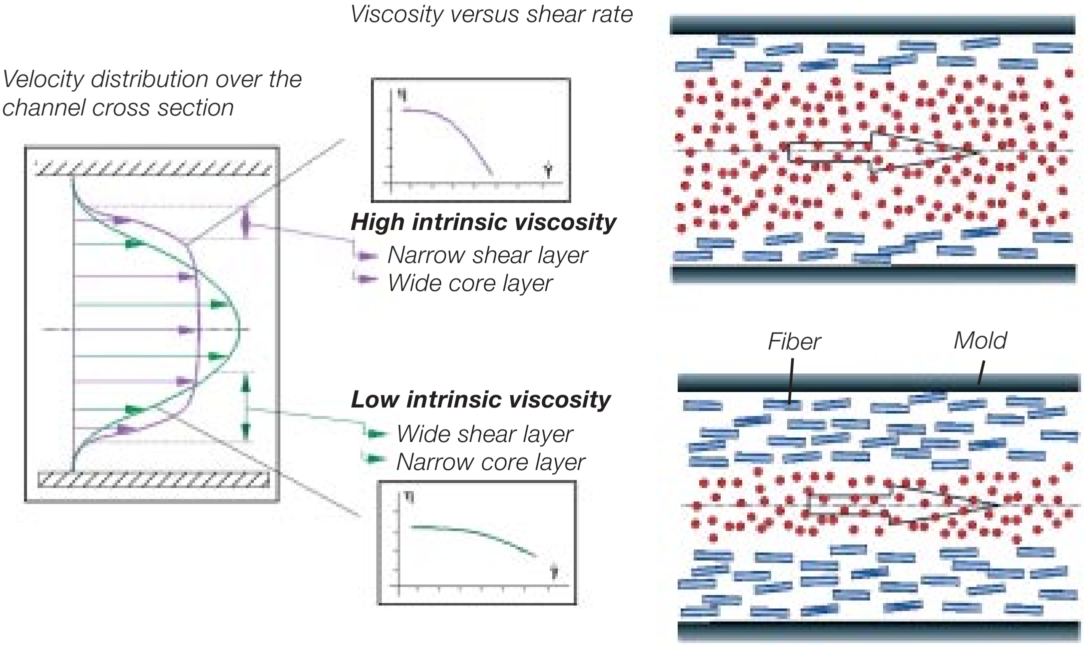



***Figure 6:*** *Intrinsic viscosity and structure of layers*

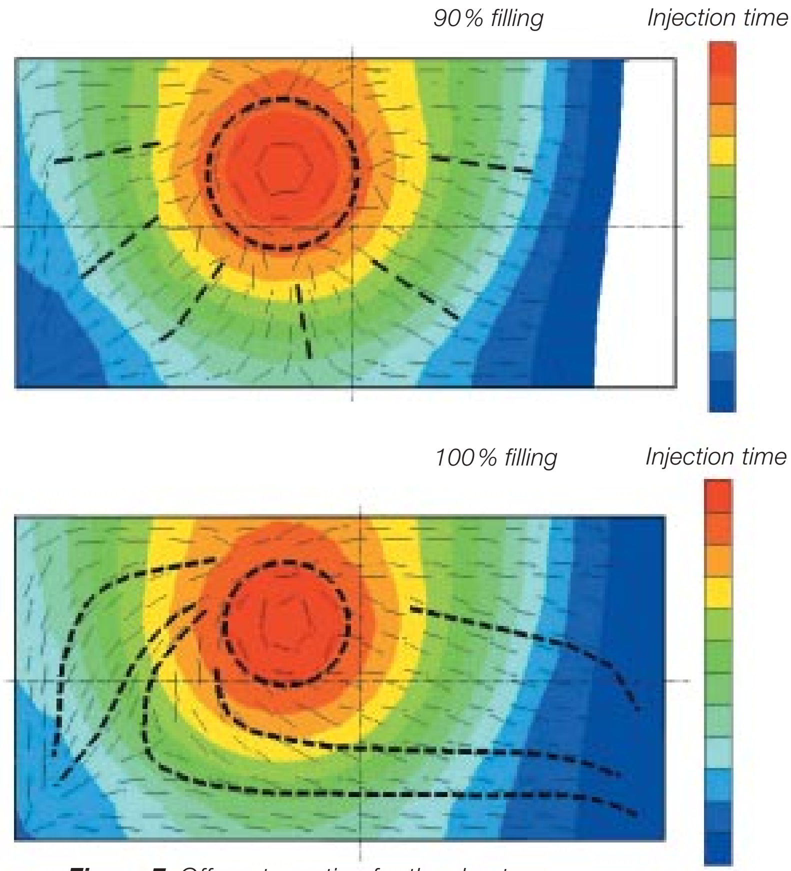



***Figure 7:*** *Off-center gating for the sheet*

***Figure 9:*** *Warpage at the end of the flow path*

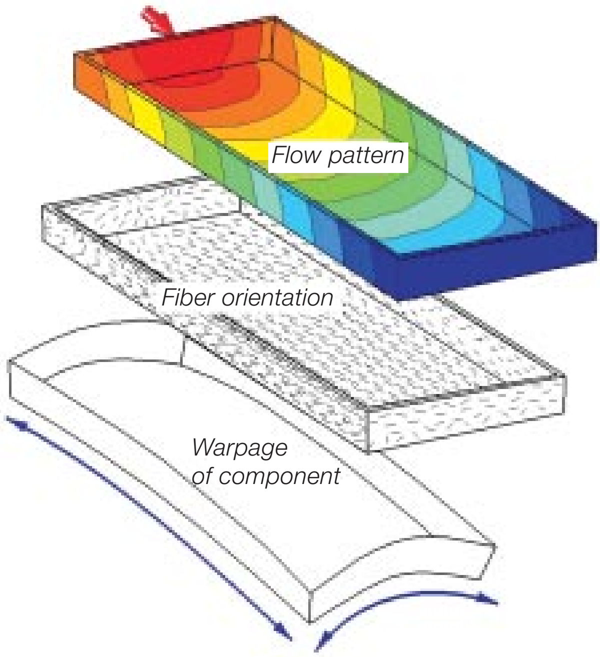
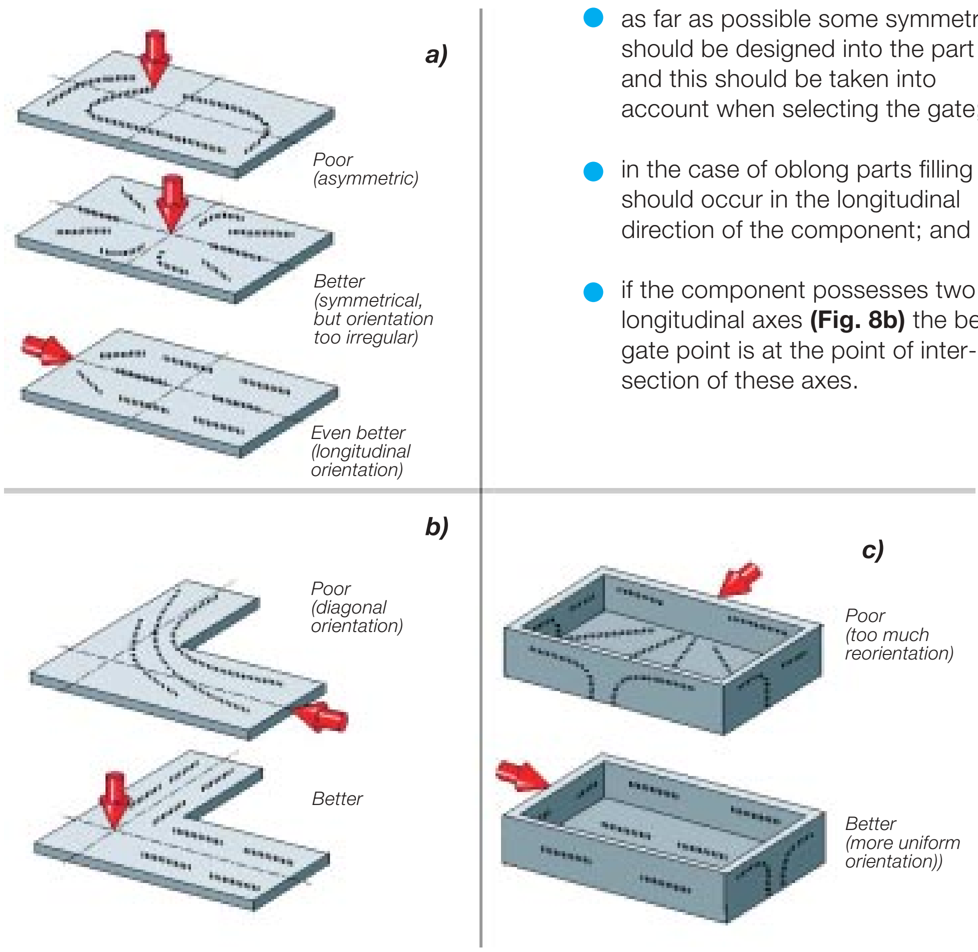



***Figure 8:*** *Gating position and fiber orientation*




The choice of gating point is thus of decisive importance and should always be done in such a way that the melt can fill the cavity without any major changes of direction. The following rules apply to this **(Fig. 8):**

- as far as possible some symmetry should be designed into the part and this should be taken into account when selecting the gate;
- in the case of oblong parts filling should occur in the longitudinal direction of the component; and
- if the component possesses two longitudinal axes **(Fig. 8b)** the best gate point is at the point of intersection of these axes.

## Transverse orientations at the end of the melt flow path

The greatest perturbation in the orientation pattern generally goes out from the end of the melt flow path **(Fig. 5, right)**. Immediately before the end of filling fibers which still have a transverse orientation are steered from the core layer into the peripheral layer. However, due to the lack of shear, reorientation no longer occurs. The orientation at the end of the flow path is uniformly transverse to the main direction of flow over a length of approximately five times the wall thickness.

The end of a flow path is not restricted to the region filled last. Any point where the melt prematurely comes to rest (e.g. in transverse ribs) exhibits a comparable orientation pattern. In the final analysis this means that fibers near the periphery always lie parallel to the edge (edge effect).

If the end of the flow path is a raised edge **(Fig. 9)** the different shrinkage of the base and edge results in arching.

In some cases this reorientation is further reinforced if the flow front does not reach the edge at the same time all across its width and the melt flow runs parallel to the edge in the final moments. As a result of this the width of the region reoriented relative to the base is usually increased. In the case of a panel reinforced at the side by walls or ribs  the following cases can be distinguished:

- Parallel end of flow path
  When the flow front runs up against the mold wall at the same time across the entire width there is no transverse flow and accordingly only a narrow reoriented strip. The differences in shrinkage at the upper and lower sides of ribs and hence warpage also are then particularly great **(Fig. 10, left)**.

- Confluence in the center of ribs
  When the melt runs ahead a little at the right and left a punctiform confluence is formed in the center of the rib. The greatest inhomogeneity in orientation occurs at this point. The deformation degenerates into a pronounced kink (see **Fig. 10, right)**.

- Lateral confluence
  Ideally the melt flows should meet in the corners. By guiding the flow parts of the base are also transversely oriented and differences in shrinkage at the upper and lower sides of ribs are not so marked **(Fig. 11, left)**.

This warpage is best avoided by avoiding ribs and walls running at right angles to the direction of flow as early as the design stage. For this purpose it is necessary to fix the position of the gate early. If transverse walls are unavoidable the following possibilities are available for minimizing warpage **(Fig. 12)**.

- Provide counterribs at the end of the flow path
  The same shrinkage is found on the upper and lower sides (up to 100 % improvement).

- Segment the end of the flow path
  Incisions in the edge prevent pressure stresses being transmitted from one segment to the next (up to 20 % improvement).

- Flute the end of the flow path
  The transmission of pressure stresses is likewise prevented by the meandering design (as in corrugated bellows). In addition, edge warpage occurs at each change of direction and this has a positive effect in this case (up to 100 % improvement).

- T-shaped flow promoter
  Transverse orientation under the base of the edge filled last is supported by a T-shaped flow promoter so that the shrinkage in this region is more uniform and there is less warpage (**Fig. 11, right**; up to 70 % improvement).

It is essential to advise against attempts at stabilizing the molding by means of further internal transverse ribs **(Fig. 13)**. Each of these ribs represents a flow path end and results in transverse orientation with the consequence of even greater deformation. Moreover, due to the stiffening action of the ribs it is more difficult to bend the part straight. If internal ribs are unavoidable they should at least be arranged diagonally.

## Weld lines

A weld line marks the end of the flow paths of two melt streams and results in the reorientations already described. If the two fronts meet in exactly parallel manner there will once again be a narrow region (approximately 5x the wall thickness) having an orientation transverse to the direction of movement of the melt front. This local disturbance tends to be quite small and results only in slight differences in shrinkage in the plane.

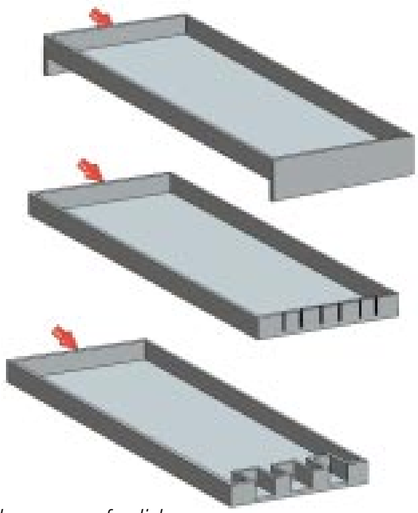


***Figure 12:*** *Design measures*

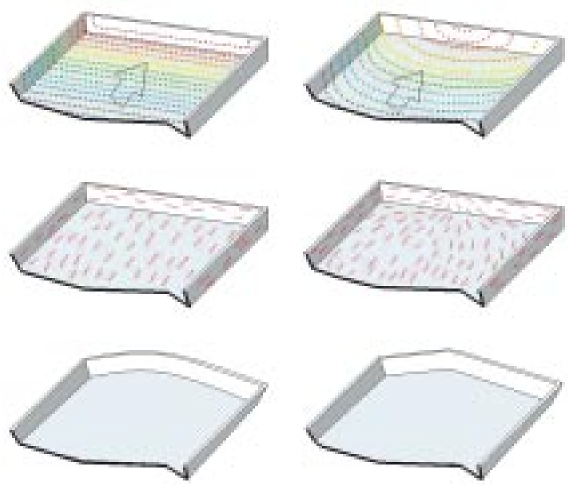


***Figure 10:*** *Filling and warpage in the case of a lid*

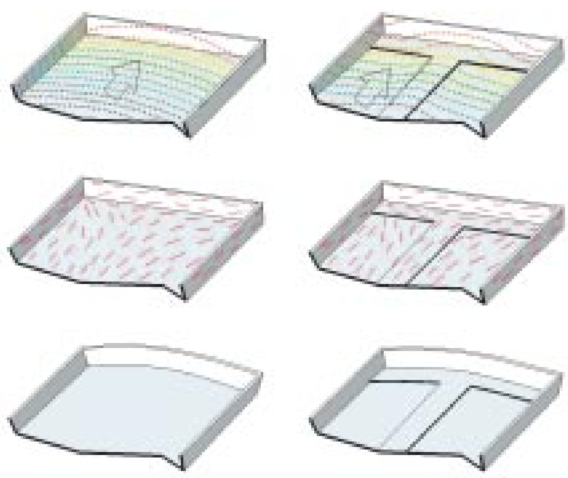


***Figure 11:*** *Filling and warpage in the case of a lid*

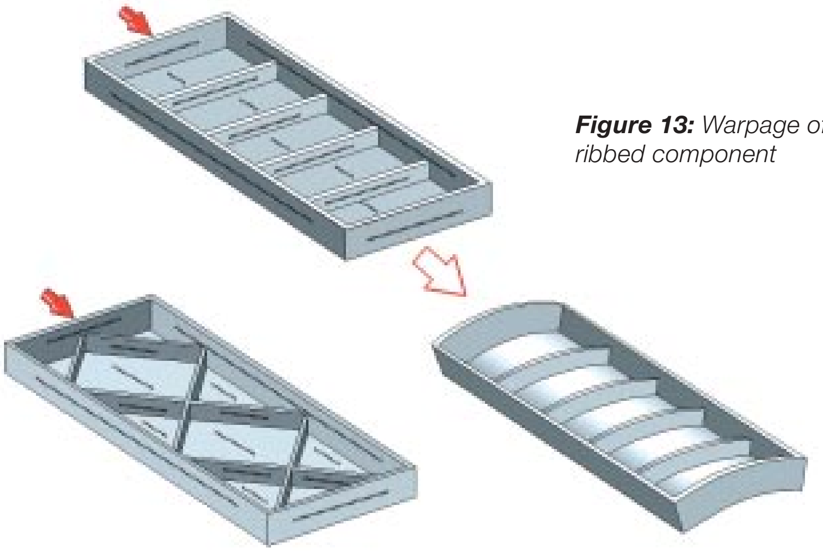


***Figure 13:*** *Warpage of a ribbed component*

In reality, however, the melt fronts almost always encounter one another at an angle **(Fig. 14)** so that starting from the point of first contact a later flow into the area not yet filled sets in. This has a serious effect on fiber orientation. In the region of first contact a wide, transversely oriented zone is found which becomes steadily narrower in the direction of the end of the flow path.

As a result shrinkage is highly variable and warpage occurs in this region.

It is absolutely essential by means of the choice of gate position to avoid the formation of weld lines in long webs. As in the example shown, it is more advantageous to displace them into the corners of the recess.

If this is not possible the weld line should be made blunt, perhaps by using flow promoters.

## Gates

Around the gate (except for film or diaphragm gates) radial flow occurs. Accordingly, a distribution of orientations will set in which is arranged symmetrically about a point. In an otherwise uniformly oriented molding the gate position is, therefore, a source of defects. The exact shape of the gate (tunnel, film, cone, etc.) has little effect on this.

The effect of the gate may be seen in **Fig. 9**. The pattern of orientation in the side wall in which the gate is located is similar to that at the end of the flow path. In both cases the fibers at the upper edge of the wall are aligned parallel to the wall, that is transverse to the orientation in the base. Thus similar warpage behavior is produced. However, the deformation is smaller close to the gate since the degree of orientation here is generally lower than at the end of the flow path.

The position of the gate can also be employed in highly selective manner to manipulate the warpage of the molding **(Fig. 15)**. Depending on whether the gate is positioned on the inside or outside of the corner the warpage of the two legs of the part illustrated is modified.

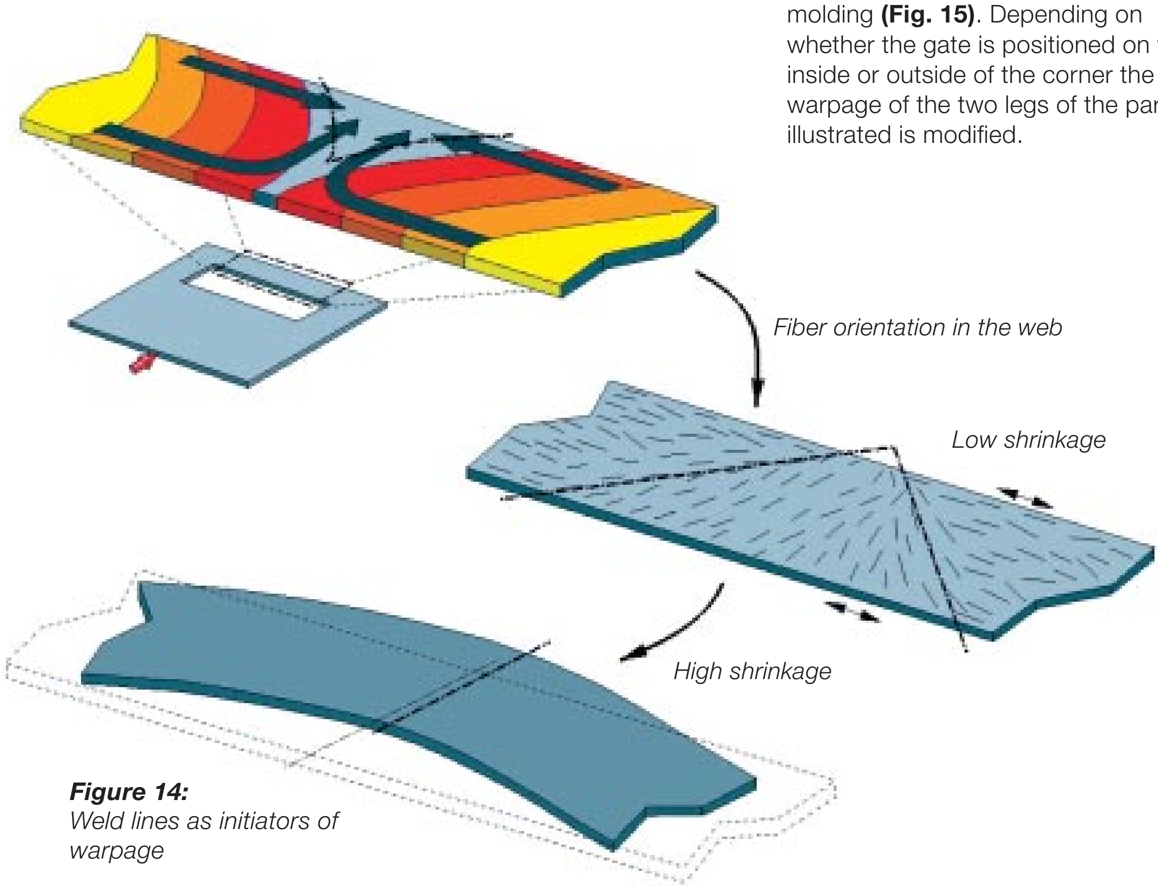



***Figure 14:***
*Weld lines as initiators of warpage*

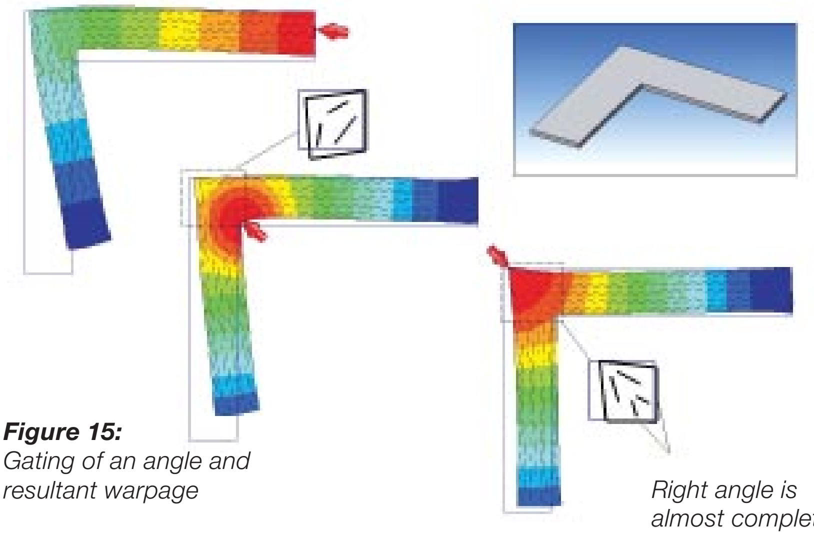


***Figure 15:***
*Gating of an angle and resultant warpage*

*Right angle is almost completely maintained*

## The material of the matrix affects warpage

A simple method for reducing the level of warpage is to use material grades having reduced shrinkage, such as those supplied by BASF, e.g. in the form of Ultradur® S. In this case the thermoplastic matrix consists of a blend with an amorphous phase which reduces volume shrinkage. This primarily affects transverse shrinkage while longitudinal shrinkage remains almost unchanged. As a result of this the difference between longitudinal and transverse shrinkage causing warpage is lower. The use of such materials will always be most successful when the degree of orientation in the part is very high.

## Simulation of molding warpage

By means of numerical simulation methods based on finite elements the filling behavior even of complex injection-molded parts can be very reliably predicted. Any possibilities for air traps and weld lines can be recognized and filling pressures and clamping forces can be estimated.

Calculations of warpage do not yet permit such quantitative statements. In the case of unfilled plastics, due to the large number of parameters having an effect (pressure and temperature history, molecular orientation, crystallization, etc.) at best qualitative predictions can be made about the type of warpage. On account of the dominant effect of the fibers warpage calculations for fiber-reinforced materials are distinctly more reliable. However, to do this it is additionally necessary to calculate the orientation of the fibers.

The potential of such simulation computations is less to do with the exact prediction of a mold correction than with the comparison of different design or gating variants. Thus causes of warpage can be found and optimization steps can be evaluated.

In order to arrive at a component having low warpage it is also necessary to have the freedom to implement the changes to the gating and molding geometry which were identified as being useful. Accordingly, CAE techniques such as warpage analysis must be used at an early stage of development.

## Summary of design rules

- Aim for a uniform direction of flow (direction of orientation).
- Gate oblong parts in the longitudinal direction.
- Aim for and/or emphasize symmetry.
- Avoid ribs or walls transverse to the direction of flow.
- Take account of transverse orientation at the end of the flow path and along edges.
- Position the end of the flow path in corners.
- Aim for flow lines which are as blunt as possible (pay attention to strength!).
- Avoid flow lines on free-standing webs or displace them into the corners.
- Retain the freedom to make changes.





KTX 9913 e 12.2000

BASF Aktiengesellschaft
67056 Ludwigshafen
Germany

BASF