From filling to warpage in 3D

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For many injection-moulded parts, 3D simulation has definite advantages over calculations using 2 ½ dimensional shell models. This article provides an overview of the new possibilities offered by the Sigmasoft simulation program.

In the development of injection-moulded parts, increasing use is being made of simulation programs which are able to calculate the mould filling, the holding pressure phase and cooling phase right up to demoulding, including the warpage of the part [1, 2]. The programs used to date for the simulation of injection moulding processes work with geometrical information which approximately describe the upper, lower or central surfaces of the actual geometry. This calculation procedure is generally referred to as a 2 ½ dimensional shell model. The only approximate description of the part geometry by a central surface could have a detrimental influence on the quality of the result. This is particularly the case with calculations for components with non-uniform wall thicknesses [3, 4, 5, 6]. Figure 1 shows schematic areas in a plastic part in which three-dimensional flow effects take place [4].

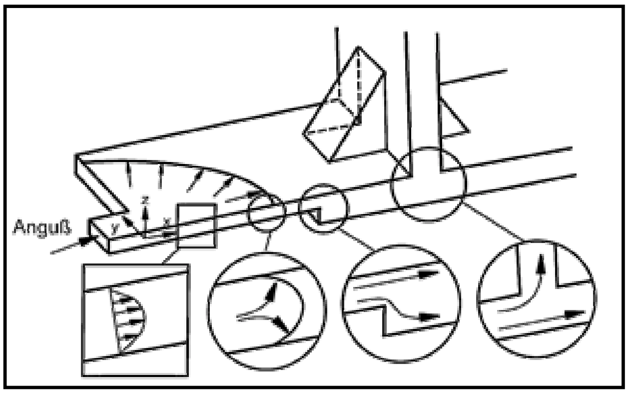


Figure 1.

Completely three-dimensional approaches to simulation for calculating flow processes have been described before. However, it has recently become possible to calculate not only the fibre orientation but also the warpage of fibre-reinforced components using three-dimensional methods.

The mould in a 3D volume model

Nowadays, volume-oriented CAD data are available for products subject to calculations in the majority of cases. These data may be read into the Sigmasoft program and fully automatically meshed in 3D.

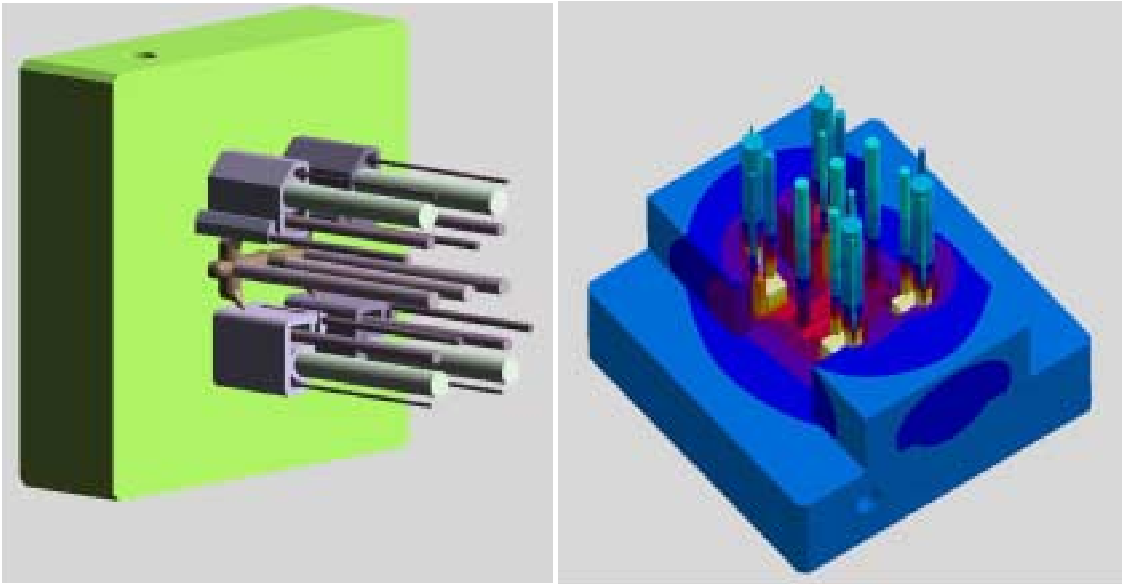


Figure 2.

In Sigmasoft the mould is three-dimensionally meshed. Figure 2 shows the structure of a mould in individual parts, including the cooling. Several cycles may be simulated in order to determine the temperature conditions of the mould in quasi-stationary state. This method enables corner effects to be calculated physically and the local impact on the part, for example on warpage, to be allowed for in the correct manner.

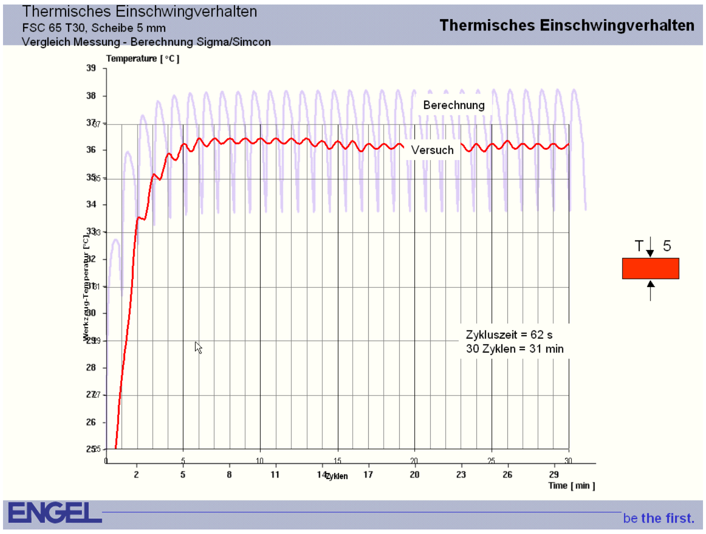


Figure 3.

Figure 3 shows the calculated temperature profile for an actual mould in a direct comparison with measurements in the factory of the injection moulding manufacturer Engel. In addition to the exact temperatures, it was also possible to predict exactly the number of cycles during the start-up process.

Overmoulding injection moulding and insert injection moulding

With overmoulded injection moulding or insert injection moulding, great interest is attached to the consideration of inserts and overmoulded parts. On the one hand, cold inserts may have detrimental impacts on the mould filling and, on the other, due to the impacts of temperature and pressure the polymer melt could have a detrimental effect on sensitive overmoulded parts. This is of particular importance with the encapsulation of electronic components. In 3D simulation with volume elements, inserts are considered as a separate material group. For example, it is possible to analyse heating-up processes on inserts.

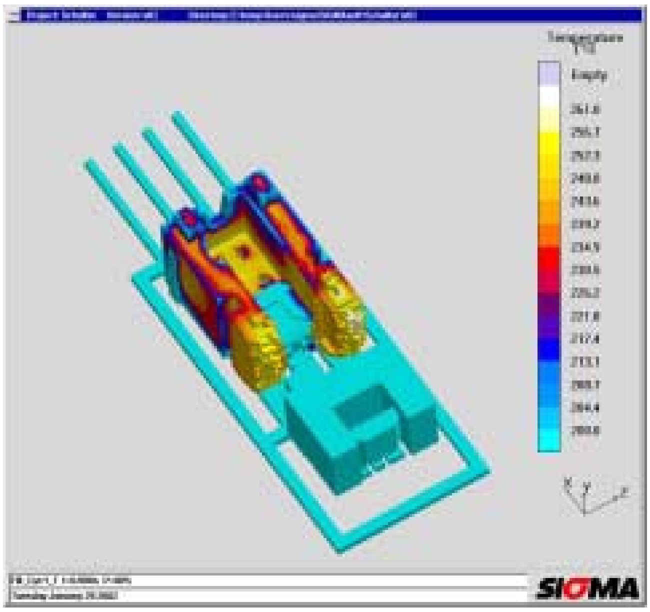


Figure 4

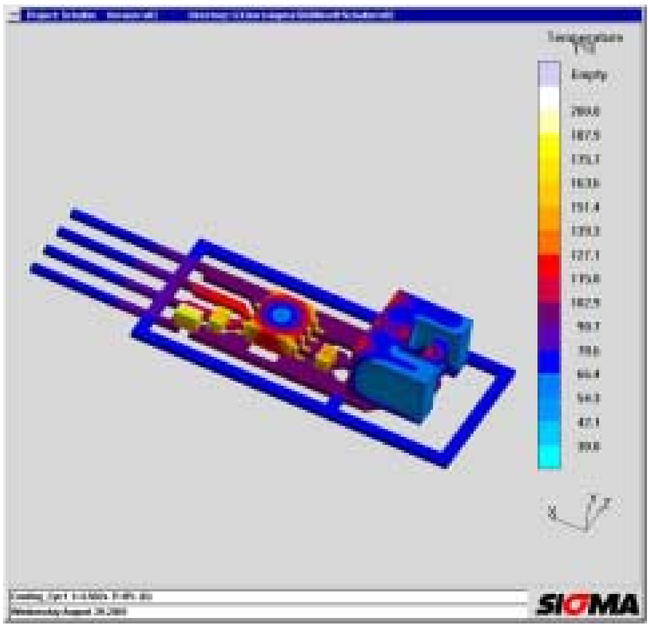


Figure 5

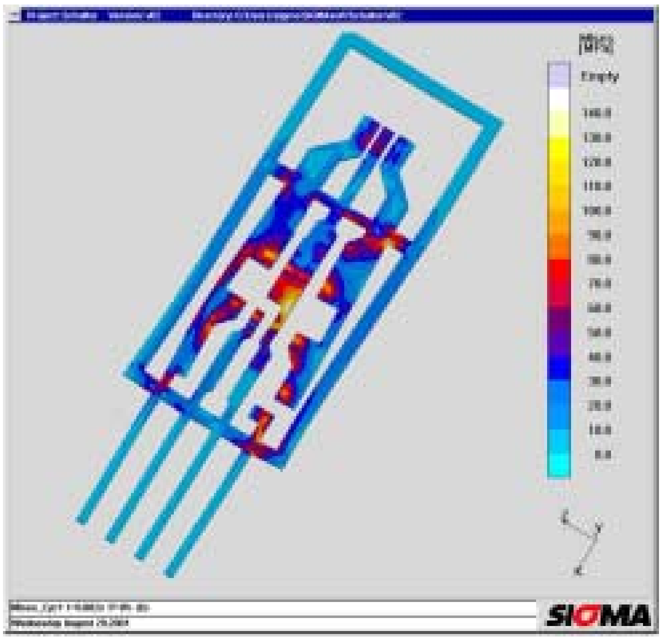


Figure 6

Figures 4 to 6 show the simulation of a switch component in which electronic components are encapsulated by a thermoplastic material. The geometry was transferred from a CAD system. Figure 4 shows the mould filling, Figure 5 shows the parts to be encapsulated. The arrow indicates a component which became detached during the injection process. The plastic melt flow heats up the solder and weakens the connection with the diode and the printed circuit board. The increased temperature results in stresses additional to the injection pressure and thermal warpage in the components and the printed circuit board (Figure 6), which also contribute to failure.

Build-up of internal stresses with a PSGA (polymer stud grid array)

PSGA components for chip manufacture have a wall thickness of a few millimetres and are encapsulated in a auxiliary frame, known as the lead frame. Figure 7 shows the calculated components. In order to exclude the possibility of non-uniform temperature distribution in the mould as a cause of warpage, a detailed 3D simulation of the entire mould, including the cooling channels, was created. The thermal simulation of several production cycles up to quasi-stationary state did not, however, reveal any significant temperature differences in the sides of the mould. Following this, the cooling of the component to room temperature and the resulting thermally induced warpage was calculated: this is shown in a greatly exaggerated way in Figure 8. This revealed that the different wall thicknesses in the component result in the premature cooling of the edge and hence the induction of internal stresses (Figure 9) which leads to warpage. A modification of the geometry of the injection-moulded part to obtain more uniform wall thicknesses succeeded in drastically minimising the stress build-up and the warpage (Figure 10).

Figure 7 (And expanded)

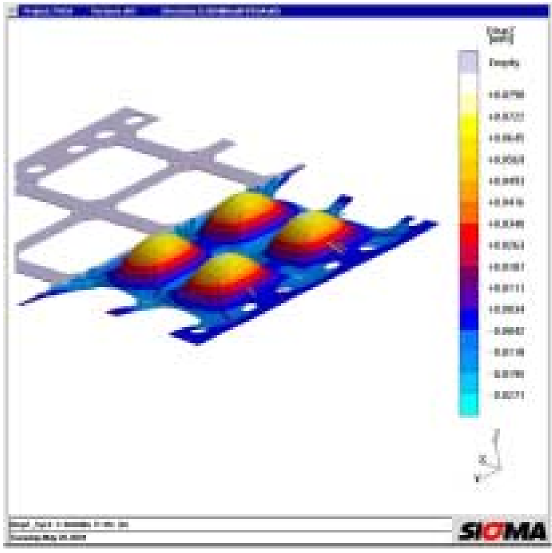


Figure 8

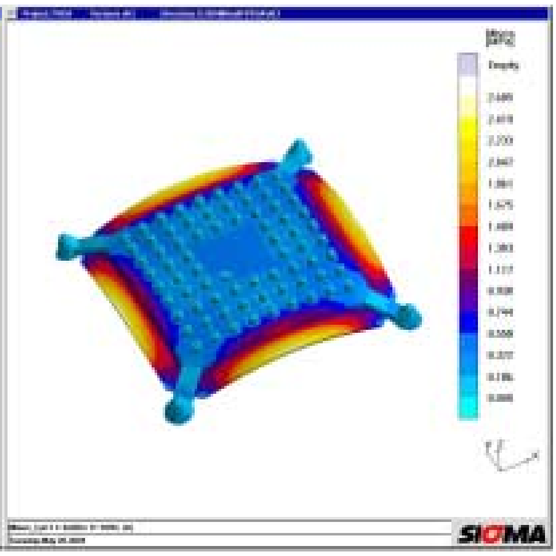


Figure 9

Figure 10

Warpage in thick-walled components

Calculations using shell models are not adequate for injection-moulded parts with high wall thicknesses; here it is necessary to use a 3D volume model. Figure 11 shows a thick-walled flange made of polyethylene with a wall thickness of 12 millimetres in which the geometry and the edge effect result in warpage. The temperature profile during cooling shows a clear displacement of the hot area towards the internal edge (Figure 12). This area solidifies later and hence pulls the sides of the flange upwards.

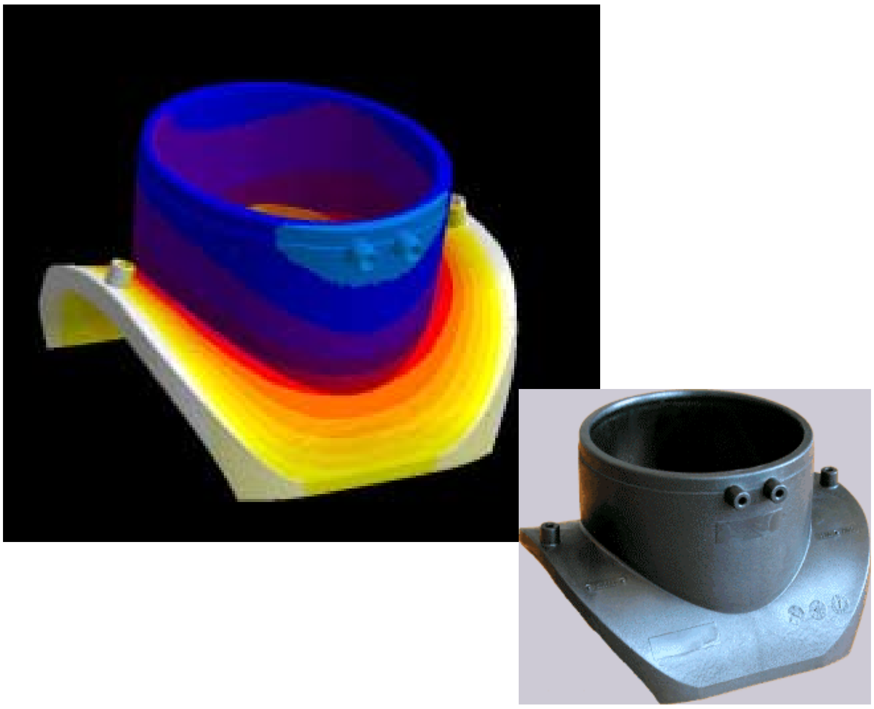


Figure 11 (And inset –actual part)

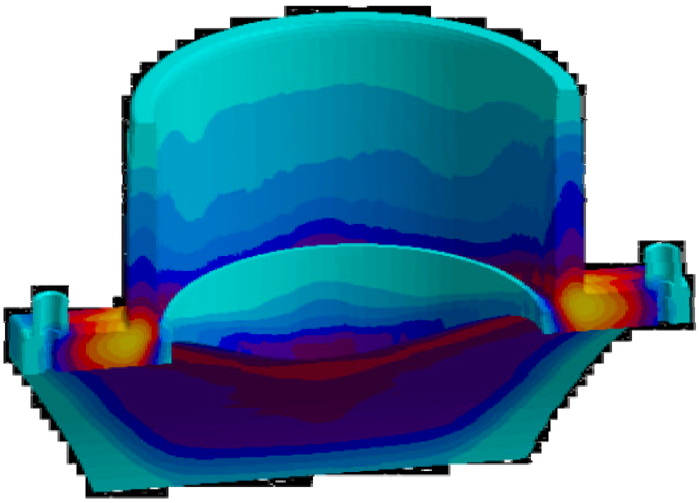
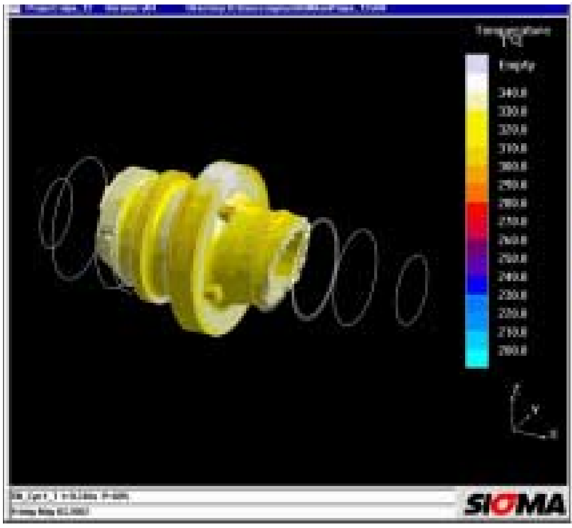


Figure 12

Predicting warpage in fibre-reinforced materials

In fibre-reinforced thermoplastics, the anisotropic material properties have a significant impact on the later warpage of the components: if the fibre orientation is defined by the gate position, only an insignificant influence on the warpage during series production may be achieved by changing the process parameters. Consequently, there is great interest in the exact prediction of the warpage behaviour of reinforced materials. Sigmasoft recently succeeded in calculating fibre orientation and warpage in 3D volume models. For this, the material data are determined using mixing rules from the data on the polymer matrix and the fibres and do not have to be re-calculated in complex experiments for each new matrix fibre mixture.



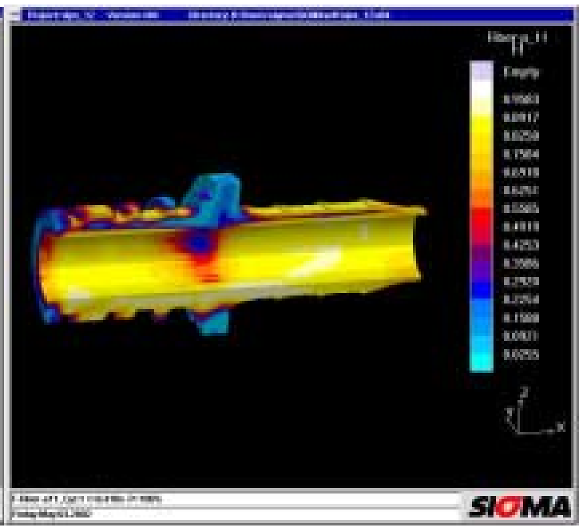


Figure 13a Figure 13b

Figure 13a shows the mould filling for a fibre-reinforced component for medical equipment. Gating from above produces different fibre orientations in the thick-wall area (Figure 13b). The colours represent the degree of orientation. Light colours indicate a high degree of orientation while dark areas represent areas with a distributed fibre orientation. While the lower area has a strong alignment in the direction of the x-axis, the upper area is orientated in the direction of the y-axis.

During cooling, therefore, warpage in a longitudinal direction during cooling will essentially take place transversely to the fibre orientation in the upper area and longitudinally to the fibre orientation in the lower area. This causes the part to warp (Figure 13c).

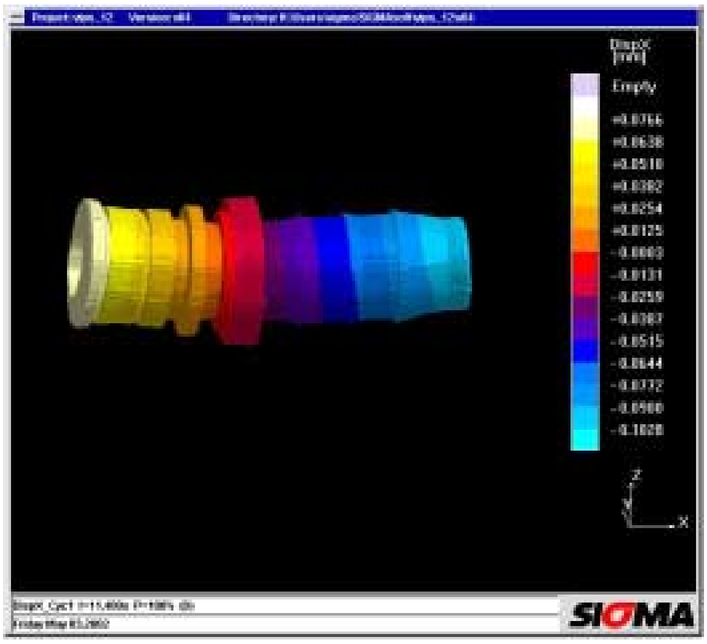


Figure 13c

If, on the other hand, the gate position is optimised and the mould filling performed from the end (Figure 14a), a symmetrically fibre orientation will become established in the thick-walled area (Figure 14b). This means that warpage occurs uniformly in the longitudinal direction and the part remains straight (Figure 14c).

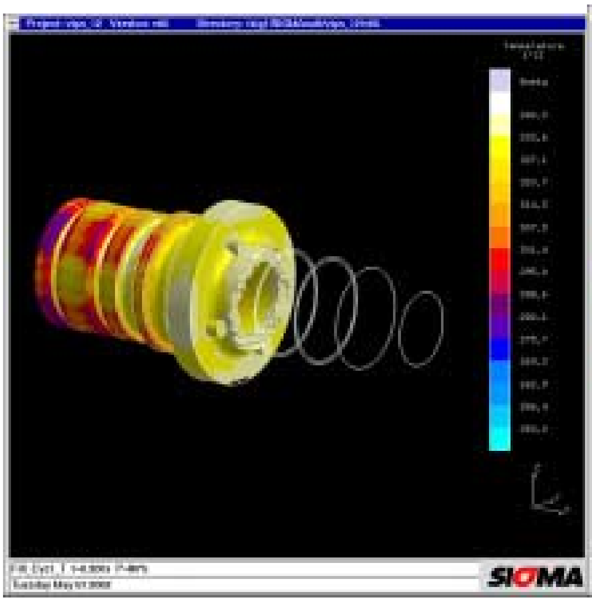


Figure 14a

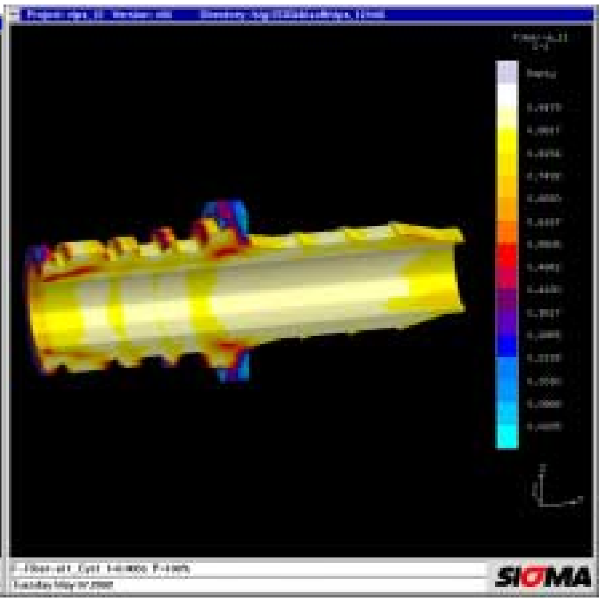


Figure 14b

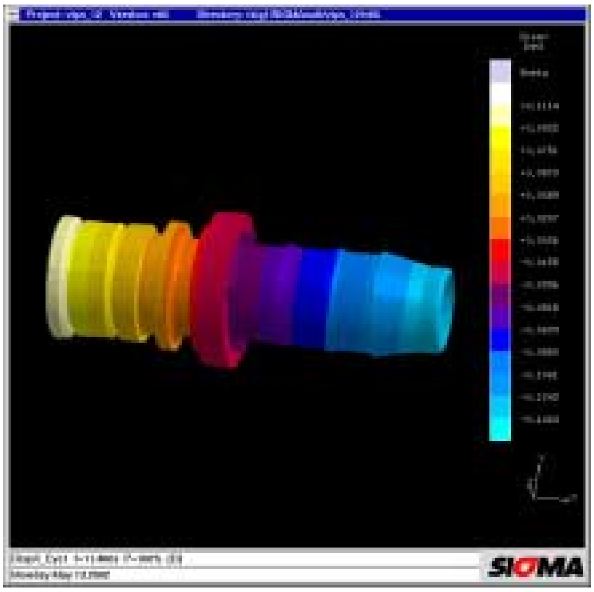


Figure 14c

Figure 15 shows another example of a warpage calculation. This is a relatively large pump housing made of fibre-reinforced polyamide. Once again, simulation confirmed the warpage of the part. Conformity between the calculated warpage values and real values was demonstrated by work performed in cooperation with the company Lüttgens in Germany. The warpage values were measured on a real component and compared with calculated values (Figure 16). In all cases, the differences were only slight and confirmed the great potential of warpage calculations in 3D volume models.

Figure 15

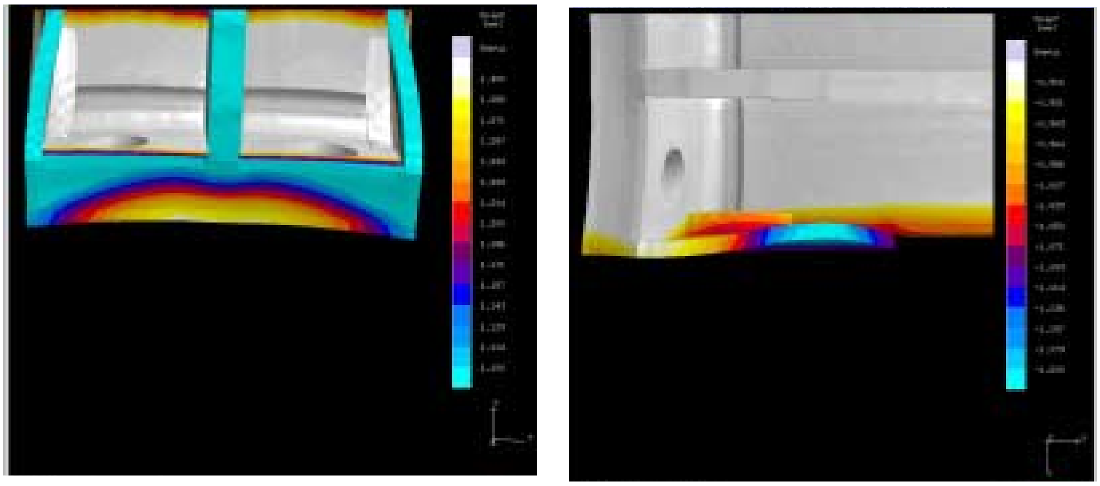
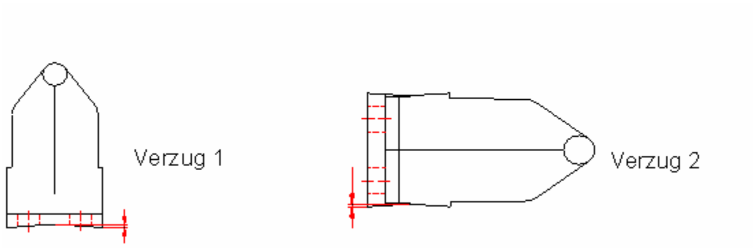


Figure 16 – Simulation and measurements (below) of anisotropic shrinkage and warpage



Länge [mm]	Breite [mm]	Höhe [mm]	Verzug 1 / mm	Verzug 2 / mm
106,52	53,74	37,08	0,20	0,25
106,54	53,75	37,08	0,25	0,25
106,56	53,74	37,07	0,20	0,25
106,47	53,76	37,09	0,20	0,25
106,51	53,74	37,07	0,30	0,25

Interfaces with FE programs

In addition to warpage predictions, three-dimensionally calculated fibre orientation may also serve as the basis for optimised component design using FE analysis, since anisotropic properties may be assigned to the material in a load case analysis. Interfaces to finite element programs are provided for this.

Outlook

Although there are still restrictions with regard to the calculation times, the results from 3D simulation with volume elements already demonstrate the advantages of using volume-orientated simulation systems:

- ⇒ there are no additional costs for model preparation, since CAD data are directly imported and meshed fully automatically
- ⇒ flow phenomena such as jetting and dead zones in thick-walled areas of parts or in areas with different wall thicknesses are described in a physically accurate manner
- ⇒ the three-dimensionally coupled calculation for the part and mould enables the thermal effects on the flow and cooling processes to be taken into account
- ⇒ the fibre orientation is calculated in 3D and may be used for part design
- ⇒ warpage is calculated directly in the 3D volume model on the basis of fibre orientation.

The quantitative calculation of warpage in fibre-reinforced parts in 3D is the subject of ongoing development work [10]. The objective is to make a tool available in the near future which may be used to predict warpage so accurately that part geometry may be optimised at the early design stage and the appropriate mould provided.

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Key to diagrams:

Gate

Figure 1: Areas of three-dimensional melt flow during injection moulding. The main drawback of 2 ½ D approaches is that flow movements in the direction of part thickness and friction in the flow plane are ignored [4]

Figure 2: The calculation of the exact temperature distribution in all areas of the mould is the basis for the correct prediction of filling, shrinkage and warpage

Figure 3: Comparison of calculated and measured temperatures over 30 cycles during the start-up process. The measured curves were transferred manually and have a low amplitude due to the inertia of the thermocouples. The start-up behaviour of six cycles to steady-state was confirmed. Photograph: Engel

Figure 4: Temperature distribution during filling. The pressure distribution and the heating-up of the electronic components were calculated in 3D

Figure 5: Local temperature distribution in the encapsulated components reveals local overheating; the soldered joint reaches temperatures of up to 160 °C

Figure 6: The temperature increase results in thermal warpage in the printed conductor. The deformation, exaggerated here, may result in the failure of the connection between the printed circuit board and electronic components

Figure 7: PSGA injection moulded part and lead frame

Figure 8: Thermally induced warpage – shown greatly exaggerated – for injection moulded part and lead frame

Figure 9: Warpage and von Mises internal stresses due to non-uniform cooling at the edge

Figure 10: Reduced von Mises internal stresses with optimised geometry

Figure 11: Thick-walled polyethylene flange and greatly exaggerated representation of warpage. Photo: Friatec

Figure 12: The warpage in Figure 11 may be attributed to the non-uniform temperature distribution "corner effect" (yellow and red areas) during cooling to room temperature

Figure 13a: Mould filling with gate position at top

Figure 13b: Fibre orientation in y-direction: the gate position at the top results in different fibre orientations in the thick-walled areas at the top and bottom

Figure 13c: During cooling, thermal expansion in the longitudinal direction is determined from the different expansion coefficients in the upper and lower areas, one transverse to and one longitudinal to the fibre orientation, cf Figure 13 b, resulting in warpage

Figure 14a: With a modified gate position, filling takes place uniformly in the thick-walled area

Figure 14b: Fibre orientation in x-direction for modified version: the rear gate position achieves uniform fibre distribution in the longitudinal direction

Figure 14c: With a modified gate position, the thermal expansion is the same at the top and bottom and the part remains straight

Figure 15: Warpage calculated in the 3D volume model for a fibre-reinforced pump housing in a direct comparison with the part. Warpage in the right-hand diagram is greatly exaggerated

Mould:		DL5546						
Part:		Fixing bracket						
Machine:		Klöckner Ferromatik FX 75			Warpage 1		Warpage 2	
Material:		Durethan BKV 30 H						
Material temperature:		270 °C						
No.	Mould temp/°C	Holding pressure, bar	Weight/g	Length[mm]	Width [mm]	Height [mm]	Warpage 1/mm	Warpage 2/mm

Figure 16: The comparison between measured and calculated warpage values reveals close correlation. The calculated values for warpage 1 are 0.2 mm and those for warpage 2 are 0.25 mm