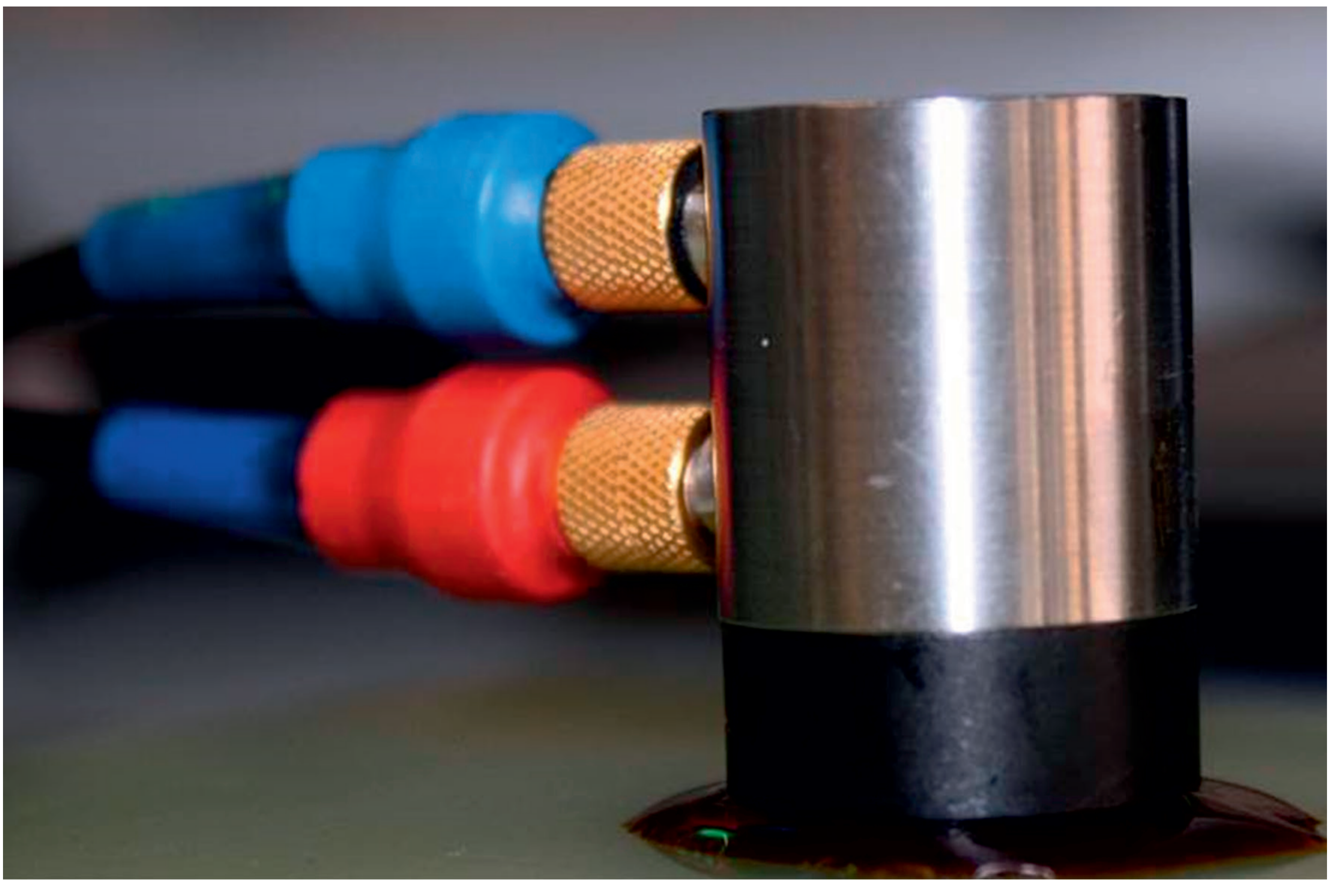
Groundbreaking Ultrasound Shear Waves

Methods for Determining the Fiber Orientation in Reinforced Plastics

A number of examination methods can be used to identify weaknesses caused by incorrect fiber orientation. In particular, the fiber volume content and fiber distribution permit conclusions to be drawn regarding the stiffness and tensile strength behavior. A new ultrasound method offers the flexibility to capture these parameters on the finished component.



Ultrasound coupling: a shear wave probe contacts a glass fiber-reinforced plastic test specimen via a viscous couplant © IKT

Additives increase the stiffness and strength of plastics in comparison to plastics without reinforcement. By correctly combining fibers with the plastic matrix, stiffness values comparable to metallic materials and considerably higher tensile strength values can be achieved.

However, the material parameters are highly anisotropic due to the fiber alignment. Reinforcement fibers made of glass or carbon for example exhibit a very high stiffness in the fiber direction. A carbon fiber's modulus of elasticity is multiple times higher under tensile stress compared to compressive stress or stress perpendicular to the fiber direction. Extremely close attention therefore has to be paid to the fiber direction when designing a component made of a plastic composite material with fiber-reinforcement.

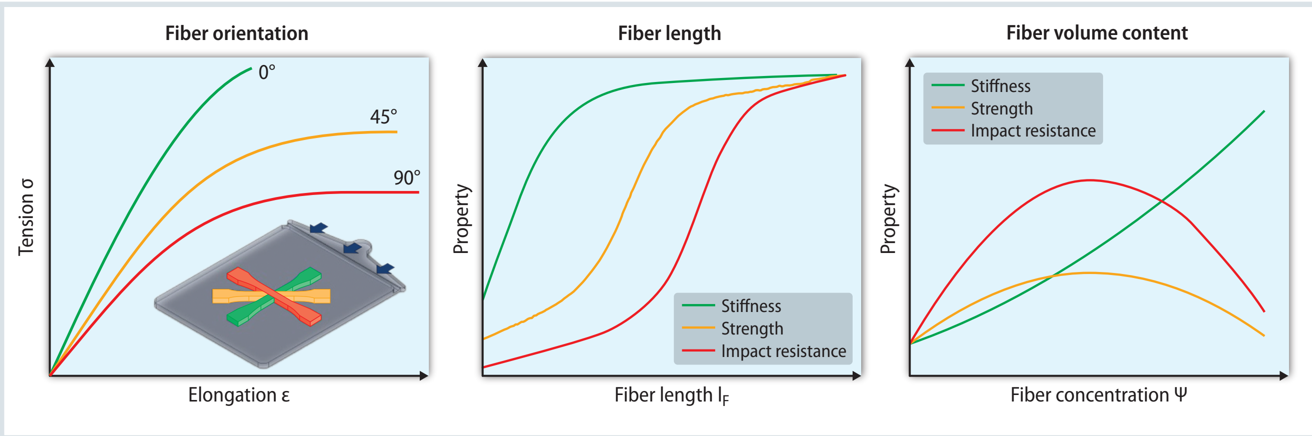


Fig. 1. Dependency of the material properties on the fiber distribution Source: IKT, graphic: © Hanser

Fiber Lengths and Incorrect Orientations

With the short fibers ranging from 0.1 to 1 mm in length that are commonly used in injection molding, the orientation is mainly determined by the mold filling behavior during the injection molding process. This is also the case when long fibers (fiber length 1 mm to 50 mm) are processed (for example in injection molding, spray lay-up or compression molding). Structural components for the aviation, automobile, or sports industry are produced with continuous filaments (fiber length greater than 50 mm). In components reinforced with continuous filaments, draping the fibers in the mold with the correct orientation is often ensured directly during production. It is however possible for fibers to be displaced during the curing process, resulting in what are known as undulations. Local areas with a low strength may develop during injection molding with short or long fibers due to unfavorable fiber orientation at joints where two melt fronts meet. Separations are possible as well when fibers accumulate on narrow structures, causing the fibers to be filtered out of the matrix.

Examination Methods

Various examination methods are available to identify such weak points due to incorrect fiber orientation. In case of continuous filaments for example, initial applications exist in which thermographic or also eddy current based methods are used. This article examines the optical method and X-ray computer tomography, which also allows valuable material parameters to be obtained beyond the fiber orientation. That is because the fiber volume content and fiber length distribution also play an important role for the stiffness and tensile strength behavior (**see Fig. 1**).

Microscopy

Polished micrograph sections of collected samples can be prepared with the help of microscopy. In order to accomplish this, pieces are removed from the component, embedded in a plastic resin and polished in several stages. Subsequently a metal layer is applied to the sample using vapor phase deposition in order to increase the contrast of the fiber cross-sections. The actually round fibers are discernible under the microscope as ellipses (**see Fig. 2**). Subsequently the orientation angle of a fiber can be determined as the ratio between the large and small axes of the ellipse.

This examination method is very time-consuming due to the required sample preparation and semi-automated evaluation on the one hand and, on the other hand, relatively inaccurate for fiber angles with only a minor deviation of the vertical orientation to the cut surface. Yet conclusions about the fiber volume content can also be drawn from the optical images. Final combustion however supplies the most accurate values for the fiber volume content.

X-Ray Computer Tomography

While the optical methods described above only supply 2D data, meaning information from only one plane of the component, computer tomography methods make it possible to determine the fiber angle in the component as a whole (**Fig. 3**). The fibers can be selected and measured with the help of software because the absorption behavior of the plastic matrix differs from that of the »

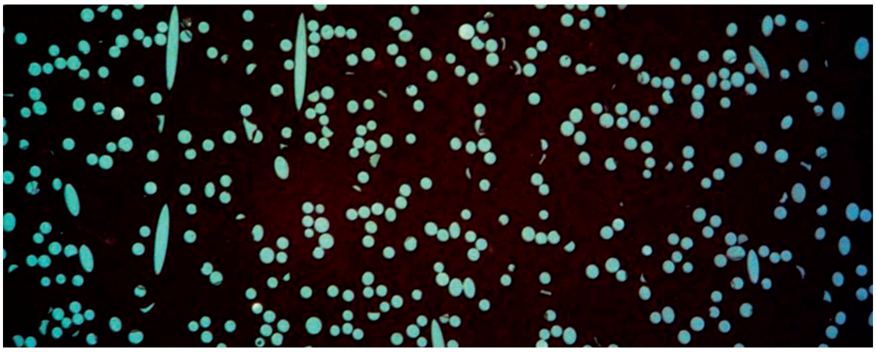


Fig. 2. Microscopy image of a polished micrograph section of a short glass fiber-reinforced plastic material. The ellipse shape is determined by the fiber orientation © IKT

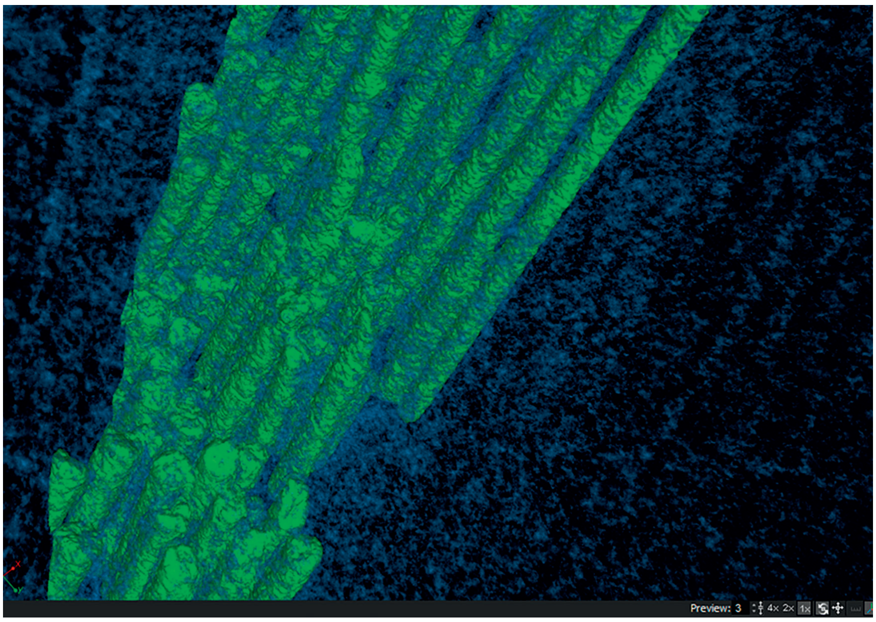


Fig. 3. Fiber bundle recorded using X-ray computer tomography © IKT

fibers. With this method, the fiber orientation in space and the fiber volume content within the sample can be determined relatively accurately. Capturing the fiber length on the other hand is a bit more complex. In the meantime however, modern algorithms enable access to these material parameters as well. This high information content comes at the cost of an often long measurement time and the sample preparation effort. In order to obtain the high geometric magnifications required to identify fibers, the sample has to be very close to the X-ray exit window. The 360° rotation required for tomography while avoiding collision with the sensitive X-ray tubes is therefore possible only with very small samples.

Ultrasound Birefringence

Another approach is to locally determine the direction with the highest stiffness and draw conclusions about the fiber direction from this. Reinforcement fibers often exhibit a stiffness that is multiple times higher in the fiber direction than that of the plastic matrix. Determining the fiber orientation by means of the local stiffness is therefore possible.

Special ultrasound probes that execute shearing movements at high frequency can incite shear waves in the test specimen via a viscous couplant. Shear waves propagate in solids at a speed that depends on the shear stiffness. When a shear wave pulse is reflected on the opposite side of the probe, the shear movement on the probe can be measured by means of the inverse piezoelectric effect. The sound velocity can be determined from the time difference between the transmitted and received pulse with a known test specimen thickness.

When a polarized shear wave is incited in an acoustically anisotropic material, the wave splits into a slow and a fast wave (for example parallel and transverse to the fiber direction). Both waves are reflected by the back wall and are superimposed when they return to the probe (**Fig. 4**).

This phenomenon known as wave splitting fails to occur only when the shear wave is polarized exactly in the direction of the fast or slow propagation speed. Thus the fastest and slowest directions can be determined through successive rotation and measurement of the sound velocity. These two directions are the directions with the highest and lowest stiffness.

Accuracy of Measurement with Ultrasound Shear Waves

To investigate the accuracy of this method, plates reinforced with continuous filaments (continuous glass filaments with epoxy resin) were produced with various fiber orientations and examined using ultrasound birefringence. Three plates respectively with two layers in the 0° fiber direction and two layers with deviating fiber directions (20° and 90°) were produced.

The test setup was realized with a shear wave probe (manufacturer: Olympus, Tokyo, Japan) with 2.25 MHz and an ultrasound generator (manufacturer: Ritec Inc., Warwick, RI/USA). The probe was moved against the test plates, pressed on, and rotated using an industrial robot (model: IRB 120, manufacturer: ABB, Zurich, Switzerland). Pulses were continuously sent to the ultrasound unit during rotation to trigger ultrasound measurements.

The comparison of the measurements on the three glass fiber-reinforced plates (**see Fig. 5**) clearly shows a difference between the various fiber orientations. A symmetrical, hat-shaped sound velocity distribution is discernible with a purely 0° orientation. The sound velocity is highest with polarization of the sound waves in the direction with the highest stiffness (0°).

When some of the layers are rotated, the high point shifts to the right. When there is the same number of layers in the 0° direction and 90° direction, there is no measurable difference in the

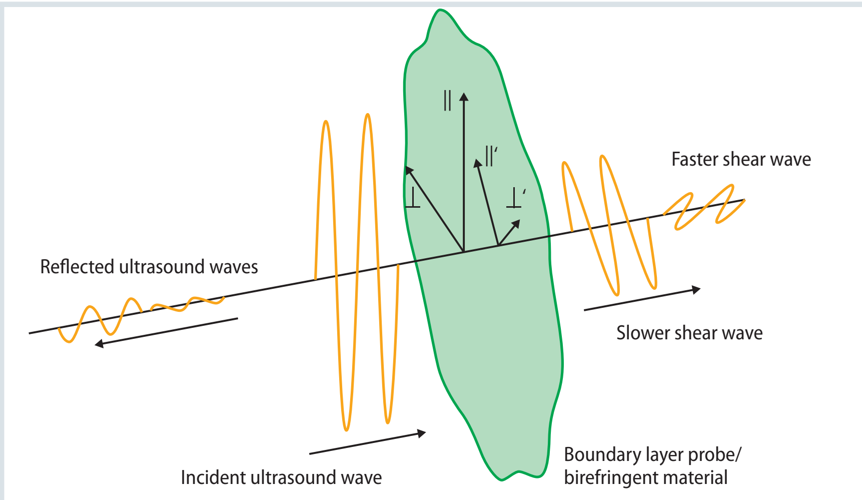


Fig. 4. Acoustic birefringence in an anisotropic material Source: IKT, graphic: © Hanser

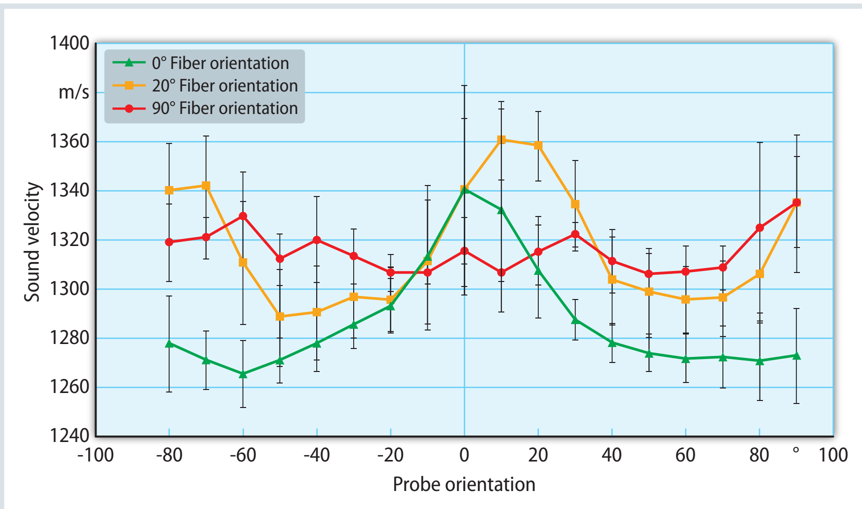


Fig. 5. Measurement of the sound velocity depending on the probe orientation

Source: IKT, graphic: © Hanser

orientation-dependent sound velocity and the result is a nearly straight line.

Examination using ultrasound birefringence is also possible with injection molding components since the fiber direction determines the stiffness here as well. Thus the fiber orientation of the reinforcing short glass fibers could be determined on injection-molded plates with thickness from 2 mm to 4 mm. An unobstructed, level surface of about 1.5 cm x 1.5 cm is needed on actual thin-walled components in order to apply the probe.

No information can be obtained regarding the fiber orientation between the core and edge layer because there is no clear boundary layer to reflect the ultrasound waves. However, a statement regarding the fiber orientation can be made on average across the thickness.

Conclusion

Various methods to determine the fiber orientation are available depending on the problem in question. Polished micrograph section analysis allows the fiber orientation to be calculated from the ellipse geometry of the fiber cross-sections. Computer tomography quickly supplies spatial information about the fiber orientation. However, both methods are associated with a relatively long measurement time and relatively complex evaluation. Ultrasound birefringence is the best choice to quickly obtain information about the fiber orientation, or when only the direction with the highest stiffness needs to be determined. The objectives of future work are to further refine the acoustic method and to improve the quantitative significance. ■

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