The Ultrasim fatigue tester, the novel test specimen for studying the fatigue strength of engineering plastics, is produced from Ultramid A3WG7 CR polyamide 66

Fatigue Strength. Choosing the right material and component design is particularly critical for plastics destined for use under the hood. Materials in this environment are exposed to pulsations for long periods of time in hot, aggressive media. For this reason, system suppliers and auto manufacturers place great importance on knowing the long-term dynamic load behavior of plastics, especially tailor-made polymers, before they are introduced into service. With a newly developed test specimen made from glass-fiber-reinforced polyamide, it is now possible to systematically study the fatigue behavior of the engineering plastic.

Components also Suffer from Fatigue

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The high mechanical and chemical stresses that modern engineering polymers are required to withstand are well known from technical specifications. However, the behavior of these polymers under long-term cyclic load, i.e. their fatigue behavior, has not been intensively studied so far. Yet a knowledge of this behavior is very important for the development of application-tailored materials. System suppliers as well as auto makers are very insistent that engine mountings, oil intake modules and other structural components and media-transporting parts exposed to pulsations show defined and predictable behavior under long-term dynamic load. This is particularly the case in highly stressed, safety-relevant applications.

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Concept of a Novel Test Specimen

After numerous preliminary studies, the experts at BASF, Ludwigshafen, Germany, came to the conclusion that there was only one possible way of obtaining comprehensive theoretical and practical knowledge of the fatigue strength of components made from engineering thermoplastics. A special test specimen for cyclic internal pressure testing would have to be designed to meet a variety of requirements. It would have to be an open, not completely rotationally symmetrical, hollow specimen, which was in no place thinner than 2.2 mm, had the smallest possible volume for later media tests and permitted the impingement of media from both inside and outside. In addition, it would have to

- withstand cyclic loading pressures up to 30 bar max.,
- have only one failure mode in its basic structure,
- fail in a defined area,
- have a typical fiber distribution at the defined weak point,
- permit size variations and the incorporation of knit lines/weld lines via slight design changes.

The material initially selected by the company for production of the new test specimen was Ultramid A3WG7 CR – a polyamide 66 formulated to withstand high dynamic load and reinforced with 35 % glass fibers. The test specimen molded from this material fulfills all the

Series of Articles

This article is Part 1 of a two-part series on the "Fatigue strength of engineering plastics" and deals with the CAE design and production of a novel test specimen. Part 2 on this subject will appear in the 2nd quarter of 2010 after the submission of further results.

above-mentioned requirements and is known as the Ultrasim fatigue tester **(Title picture)**. This designation indicates that the determination and validation of comprehensive material data with the new test specimen go hand in hand with the development of a numerical model using the now universal BASF simulation tool, Ultrasim.

Pre-requisite: A High-quality Plastic

For the first Ultrasim fatigue tester, BASF chose Ultramid A3WG7 CR – a grade from the CR range launched in 2007. This material, like the other representatives of this part of the polyamide range, is precisely adjusted to service requirements under high dynamic loads using Ultrasim. Such loads occur, for example, in vehicle crashes but also in components such as engine mountings, which are exposed to continuous vibrations. These materials are sufficiently stiff, strong and heat-resistant, have high energy-absorbing capacity and, above all, can be precisely described with sophisticated CAE software. The CR products come with the necessary material data for simulation, i.e. data on behavior at high strain rates and modeling of failure as a function of fiber orientation. The optimized formulations of these plastics permit narrow material specifications, which are subject to intensive quality control and are the basis for material approvals by the OEM.

Material characterization was carried out on EMI (Ernst-Mach-Institut) tensile test bars and resulted in material Wöhler curves, which will be described in detail later. In Wöhler curves, the maximum stress or stress amplitude of the dynamic load is plotted on a double logarithmic scale against the number of load cycles achieved. Both metals and plastics produce an S-shaped curve with flat initial and end portions **(Fig. 1)**.

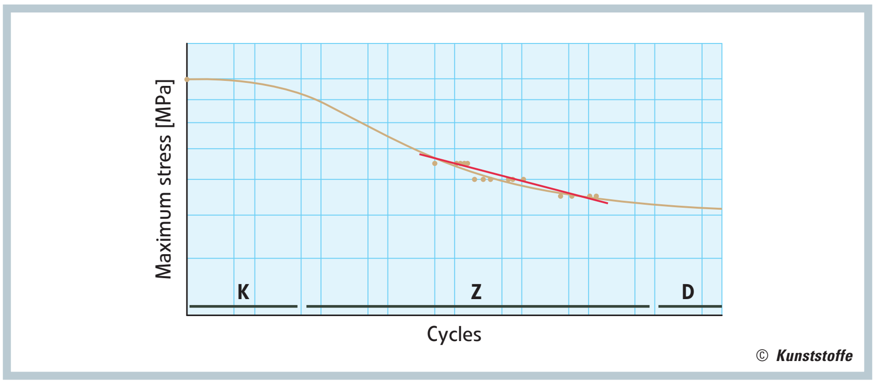


Fig. 1. The path of a Wöhler curve can be approximated in the center of the curve by a straight line with a negative gradient, the so-called Wöhler line. The fatigue endurance strength range (Z) lies in the region of this Wöhler line, i.e. the stress at which the part fails can be obtained as a function of the type of load and number of load cycles to be achieved. To the left of this region is the short-term strength range (K). Here the component still approximately achieves the initial, high static fracture load. At the other end of the scale, i.e. above several million load cycles, the curve becomes significantly flatter again (D)

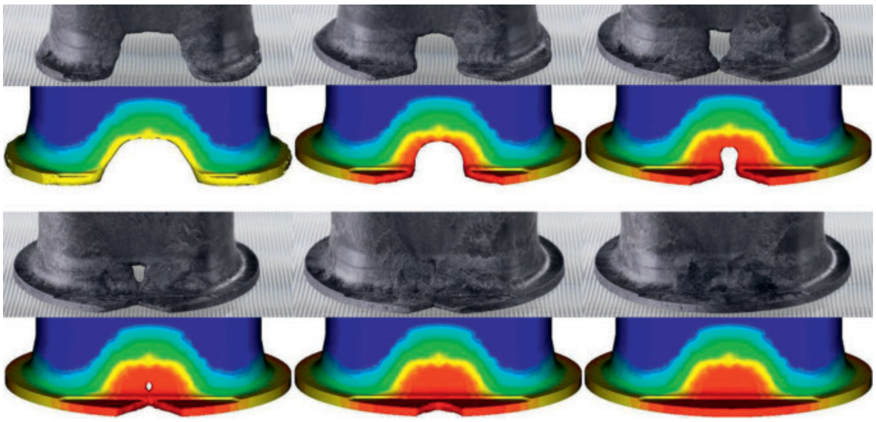


Fig. 2. Filling simulation and real filling behavior of the Ultrasim fatigue tester specimen

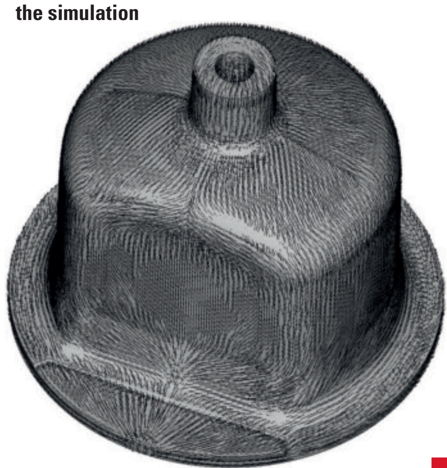
Challenge: CAE Design of the Test Specimen

The requirements that the test specimen had to meet presented an enormous challenge for CAE design optimization. The approximately rotationally symmetrical geometry and spherical cap result in large, highly stressed zones that permit the specimen to have various failure sites or modes, depending on the position of material or production-induced weak points such as voids or surface defects. To complicate matters further, with fiber-reinforced materials, the influence of the manufacturing process on mechanical properties must also be taken into account [1 to 3].

Virtual design and optimization of the test specimen were carried out using Ultrasim [4] and involved not only simulation of the production process but also strength analysis with integrative simulation and mathematical component optimization. The load criterion was a static internal pressure that would lead to failure at a maximum of 40 bar. The requirement for failure at a defined point was achieved by introducing a flat area in the cylindrical part. In the edge zones of the flat area, there is a highly stressed region where a circumferential stress is superimposed on a flexural stress. Since local fiber orientation and weld lines have a considerable influence on local strength behavior, it is essential to include them in the design.

To avoid other knit lines, the test specimen is centrally gated on the top in the area of the thread. The results of the filling simulation are shown in **Figure 2** together with the filling study on the actual test specimen. It can be seen that a certain slowing of the melt in the flat area is unavoidable because of its reduced wall thickness. To achieve robust behavior of the test specimen, the local wall thickness must be dimensioned so that the melt fronts merge at the base of the test spec- →

Fig. 3. Fiber orientation of the test specimen in the simulation



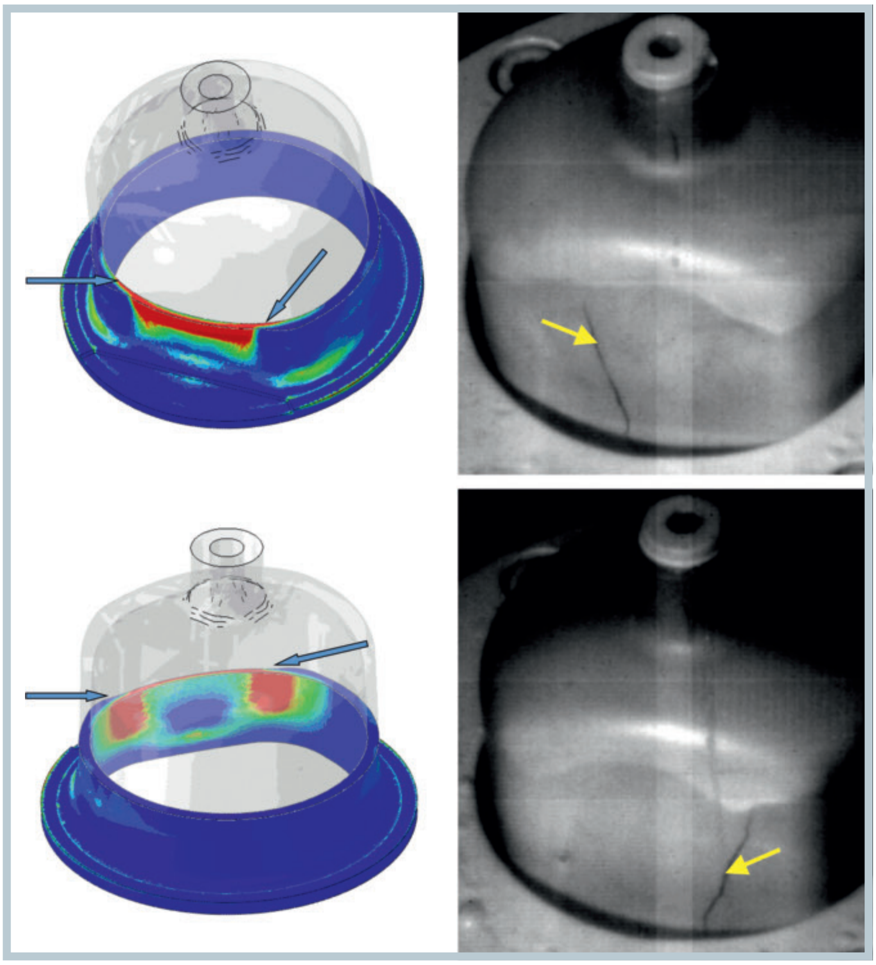


Fig. 4. Left: local material stress; in the red areas the material is overloaded (the arrow designates the critical zone: above, the test specimen is viewed from outside, below from inside); right: high-speed photographs of failure, crack initiation (the arrow designates the critical zone)

imen. The resulting fiber orientation distribution is shown in **Figure 3**. The slowing of the melt in the flat area and convergence of the melt fronts at the base produce typical wedge-shaped fiber orientation.

The strength analysis under static internal pressure shows the critical zones. In **Figure 4 (left)**, the local stress level in the material can be seen as a function of the load condition and local material properties. In the red areas, the material is overloaded and damage occurs. This damage is critical in the flat area and the transition zone from the flat area to the cylindrical part of the test specimen. Here, the overloaded zone extends throughout the total wall thickness of the test specimen and initiates failure. At these points, the test specimen fractures over the entire cross section, which is confirmed by high-speed photographs **(Fig. 4, right)**. Within an approximately 5 mm-wide zone on the left or right side, a local crack starts. The experiment confirms this reproducibly. This stable failure behavior can be observed in both static and dynamic tests.

During the development of the test specimen, many geometrical variations were considered, in which failure occurred in several regions at the same time, e.g. in the curved areas in the transition to the flange or to the threaded section. Through systematic use of optimization tools and failure modeling with Ultrasim, the shape and process were optimized so that the test specimen in its final version had – as intended – only one failure mode at a defined point.

Production of the Test Specimen: Optimum Production Parameters

Parallel to the CAE design process, the optimum production parameters had to be determined. This is because the macroscopic properties of the Ultrasim fatigue tester depend not only on the plastic used but also to an important extent on processing factors. Therefore, process control in the injection molding process plays a key role. In order to obtain reproducible and meaningful results from the planned series of tests, all injection molded parts have to have identical properties.

The most important criterion is the bursting pressure obtained. In the Wöhler test, pressure deviations of just a few bar can lead to the specified number of load cycles to bursting either not being reached or being exceeded many times over. This then makes adequate selection of the stress amplitude and therefore accurate test planning difficult.

As is evident from the filling studies **(Fig. 2)** and in **Figure 5**, the different wall thicknesses of the test specimen lead to a complex filling pattern. Through skillful choice of machine settings, it is possible to influence the position of the knit lines and especially of the point where the flow fronts merge. At higher melt temperature or injection rate, melt viscosity is decreased by the higher shear. The melt then flows more quickly into the thin-walled areas and the point where the melt flow fronts converge moves towards the end of the flow path, while the knit lines are shifted outwards.

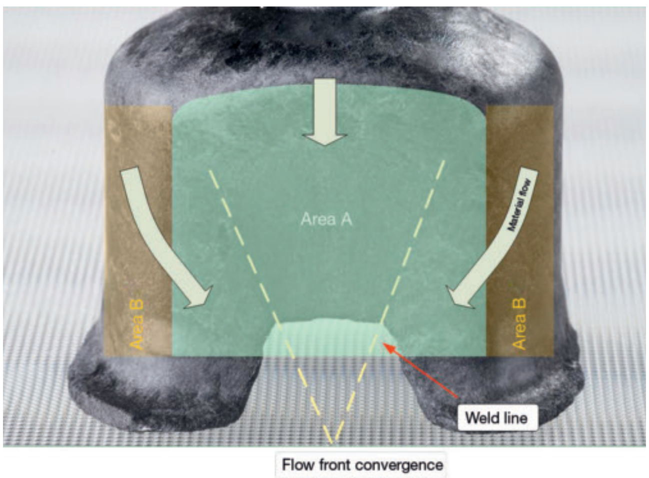


Fig. 5. Melt flow in the production of the test specimen: the melt naturally flows into the thicker-walled areas B faster than into the thin-walled area A and speeds ahead there. A V-shaped weld line is formed with the three flow fronts merging directly above the component base

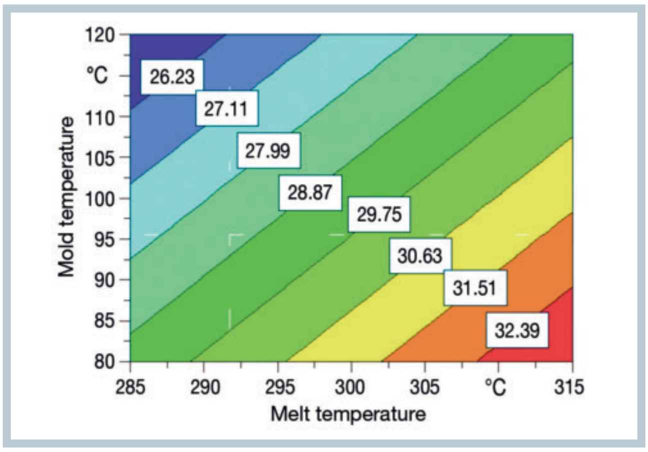


Fig. 6. Bursting pressure as a function of melt and mold temperature at high injection rates (bursting pressures quoted in bar)

These effects in component morphology are manifested in the bursting pressure of the components. To quantify the effect of the machine parameters and determine the optimum processing point for production, a full factorial 2^3 test plan was used and the melt temperature, mold temperature and injection rate were varied. Previous screening tests had shown that other machine parameters have no significant effect on bursting pressure.

The result is shown in **Figure 6**, where the bursting pressure determined for the test space is plotted against melt and mold temperature at a constant injection rate. The influence of melt temperature on bursting pressure is plausible; as expected, a lower melt viscosity shifts the flow front convergence point towards the end of the flow path. At first, the influence of mold cavity temperature was surprising. Against all expectations, lower values – which would tend to hinder the flowability of the plastic – led to higher bursting pressures. This can only be explained in terms of the complex interaction of the three flow fronts. As a result of the high injection rate, the melt is highly sheared in the thin-walled area and the cooler mold temperature is of relatively little consequence. The rapid flow of the melt fronts from the thick-walled regions, is thus compensated.

Besides selecting the right test equipment, constant monitoring of the injection molding process is necessary. To produce moldings of consistent quality, the changeover from the injection to the holding pressure phase is initiated by a mold internal pressure sensor. This measure makes it possible to recognize and compensate for wear of the non-return valves. In conjunction with pressure monitoring in front of the screw, it also provides an indication of viscosity variations in the material (e.g. as a result of non-uniform drying).

Conclusion

With the newly developed, patented test specimen, the Ultrasim fatigue tester, and previously acquired initial knowledge of the fatigue behavior of the high-strength materials in the BASF range, all important parameters affecting the fatigue of plastic components can now be systematically determined. The focus will be on the influence of stress, stress amplitude, R ratio and load frequency, temperature and temperature changes, and the presence of media such as oil, fuel and coolants. From the gradients of the Wöhler curves in the fatigue endurance strength range, engineers will gain vital information on the fatigue behavior of real components as a function of real parameters. This knowledge will in future lead to further improved and more specific material selection and component design. ■

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