Fatigue of Short Glass Fiber-Reinforced Technical Thermoplastics

High Frequency Fatigue

Short glass fiber-reinforced plastics are widely used in structural and housing components that are permanently exposed to vibrations with frequencies up to around 10^3 Hz. In order to enable appropriate dimensioning against high-frequency vibration loads, the influence of frequency on material fatigue is investigated in this work.

Whether in kitchen appliances or in the automotive sector: thermoplastics are often exposed to heat and vibrations during their lifetime.

A recent study by the Institute for Plastics Processing (IKV) in Industry and Craft at RWTH Aachen University, Germany, analyzes the influence of frequency on the fatigue of short glass fiber-reinforced technical thermoplastics. Up to now, the fatigue strength has been mainly investigated on fiber-reinforced structures, which have to withstand dynamic-cyclic loads with high amplitudes at frequencies below 1 Hz throughout the entire service life of the component. However, flat structures such as air ducts, filter and battery housings in the automotive sector, and molded parts (e.g., drills and kitchen appliances in the household sector) are different from structural applications of that kind [1]. The load conditions of those components are characterized by low load amplitudes, but high-frequency vibrations. Since the structural response under vibration is a function of the excitation frequency (modal response), component development must be carried out in accordance with vibro-acoustic considerations [2].

The vibro-acoustic structural behavior is dependent on the viscoelastic material properties, the component geometry, and the boundary conditions. If the component is subjected to excitation in the range of the characteristic natural frequency, resonance peaks occur in the structure, which can lead to high local material stresses [2, 3]. The natural frequencies are primarily determined by the component stiffness. The magnitude of the structural response, on the other hand, depends on the material damping. During component development, the prevention of the resonance case is often the objective. For this purpose, the component stiffness is optimized in such a way that the natural frequencies are higher than the excitation frequencies. The prediction of the stiffness behavior of fiber-reinforced components can be carried out using integrative calculation methods and is already established in the industrial environment [1, 4].

In many applications, however, excitations in the range of natural frequencies cannot be completely avoided due to the complex loads that occur (frequencies up to 10^3 Hz). In such cases, component approval is achieved by means of shaker tests of prototypes close to series production, since the dimensioning fundamentals for a simulative estimation of the fatigue strength are insufficient. For classical fatigue strength computations, fatigue data from Woehler testing at frequencies up to 10 Hz are used. However, these fatigue data cannot be transferred to loads at high frequencies, since the mechanical behavior of thermoplastic materials strongly depends on the loading condition due to the viscoelastic properties. In order to make this frequency range available for simulative dimensioning in the future, it is necessary to investigate the influence of frequency on material fatigue for short glass fiber-reinforced plastics.

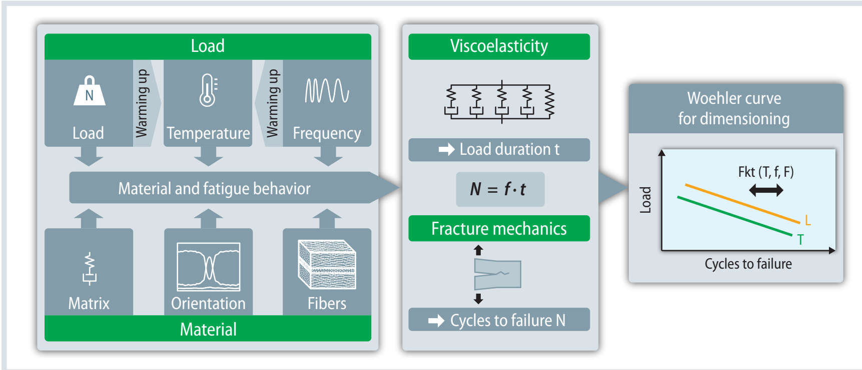

Fig. 1. Factors influencing the fatigue of short glass fiber-reinforced thermoplastics.

Source: IKV; graphic © Hanser

The Interaction of Load Duration and Frequency

In general, the term fatigue refers to the progressive damage process in the material due to repeated cyclic loads. In the case of short glass fiber-reinforced thermoplastics, the damage process primarily takes place at the micromechanical level, which is characterized by the interactions between the fibers and the matrix (**Fig. 1**) [5]. When the material is subjected to an external dynamic-cyclic load, the fatigue behavior at the micro-level is dominated by time-dependent creep effects due to the viscoelasticity of the matrix and cyclic crack growth. With continued exposure, damage accumulation occurs in the form of crack initiation and propagation. As soon as a critical crack length is reached, the stress exceeds the local bond strength and sudden structural failure occurs [6].

Load frequency is important in material fatigue in two aspects. First, the frequency constitutes the relationship between the two driving variables, the load duration and the number of load cycles. Since crack growth scales with the number of loading cycles, a higher frequency in the same time period leads to higher material damage. On the other hand, with each load cycle, a part of the applied kinetic energy is dissipated into thermal energy due to material damping (hysteresis) [7, 8]. Consequently, the loss power in the material increases with the frequency. Due to the low thermal conductivity of plastics, the thermal energy cannot be sufficiently conducted and, therefore, the material heats up at high load frequencies and fatigue process is accelerated as a result.

Frequency Dependent Fatigue

A short glass fiber-reinforced polyamide 6 of type B3WG12 HSP from BASF SE is used for the investigations of the frequency influence. The specimens are in accordance with the 1BA geometry as per DIN ISO 527 and are extracted from injection-molded specimen plates in the main direction of melt-flow. The frequency influence on the material fatigue is investigated by using force-controlled fatigue tests in the tensile range at the frequencies 5 Hz, 20 Hz, 40 Hz and 60 Hz. The stress levels are chosen in such a way that the fatigue strength range from 10^3 to 10^6 load cycles is achieved. To ensure a constant ambient temperature of 22.5 °C, the tests are carried out in a temperature chamber. In addition, the development of the specimen temperature over the entire test duration is logged using a pyrometer.

The results obtained from the fatigue tests are shown in **Figure 2**. The failure load cycles achieved in the fatigue tests show a clear frequency dependence. In the single logarithmic plot, the data for 5 Hz to 40 Hz are characterized by an almost linear relationship between the load level and the number of cycles to failure. The 60 Hz curve, on the other hand, is distinguished by a degressive trend. If the material is subjected to higher frequencies, the fatigue life is significantly reduced. When compared to the 5 Hz Woehler curve, the difference can be up to 1.5 decades. The highest number of cycles to failure (2.7 million to 4.8 million load cycles) is achieved, considering the number of tested specimens, at a frequency of 20 Hz.

Since the mechanical behavior of thermoplastics is significantly influenced by the prevailing material temperature, the fatigue evaluation needs to take into account the temperature development in the material. **Figure 3** on the left shows an example of the temperature curves at a load of 76 N/mm^2 for the different test frequencies. The Woehler experiment »

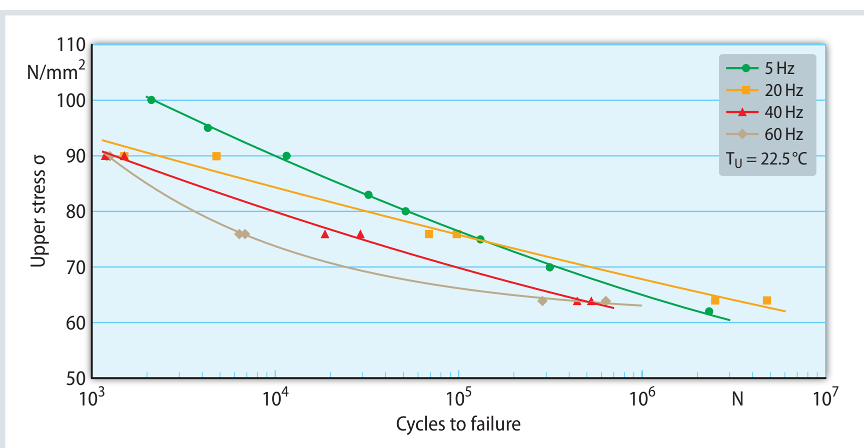

Fig. 2. Frequency-dependent fatigue data obtained from Woehler experiments.

Source: IKV; graphic © Hanser

at 5 Hz shows no increase in temperature, so that the material surface corresponds approximately to the ambient temperature. However, as the test frequency increases, the thermal dissipation in the specimen also increases. Consequently, the material temperature is rising until thermal equilibrium is reached. From this point on, no further heating takes place, and a constant temperature level is maintained. However, if the heat loss in the material is so high due to the high frequency that no thermal equilibrium with the environment is achieved, there will be continuous heating. Therefore, the difference between the averaged temperature over the test duration and the maximum occurring temperature can be used as an indicator of whether a quasi-static thermal state is established or the material exhibits temperature-induced failure. In the case of the 60 Hz test at 76 N/mm², for instance, a temperature difference of approx. 20.6 °C is reached before the specimen fails prematurely due to temperature-induced material softening (**Fig. 3, right**). At the same time, this test point is also distinguished by the highest average temperature of approx. 60.4 °C. This is different from the other test frequencies with regard to the cycles to failure and, therefore, causes the Woehler curve for the test frequency 60 Hz to become degressive.

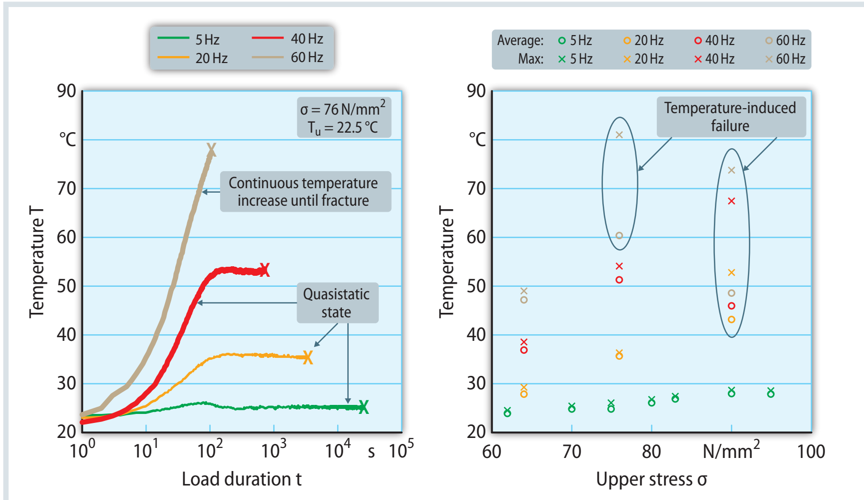

Fig. 3. Influence of the frequency on the evolution of the material temperature during the fatigue experiments. Source: IKV; graphic © Hanser

In summary, the reduction in fatigue life at high frequencies results primarily from the increase in material temperature due to the increased dissipation and the accompanying reduction in strength. Although a higher number of cycles to failure is achieved for the frequency of 20 Hz and the upper stress of 64 N/mm² than for the 5 Hz fatigue tests, it can be assumed that at high frequencies the influence of the stress duration dominates and the number of cycles to failure plays a subordinate role in fatigue. Therefore, for future dimensioning regarding fatigue strength, it is suggested to use the fatigue life over time as a design parameter instead of the cyclic life (**Fig. 4**).

Conclusion

The investigations showed that increasing the test frequency leads to a significant rise in the material temperature and thus accelerates the fatigue process of short glass fiber-reinforced thermoplastics. Furthermore, a differentiation must be made between thermal fracture and thermal quasi-stationary fatigue. An additional consideration of the temperature development in the material could improve the modeling quality of future fatigue calculation methods for high-frequency vibrating structures. ■

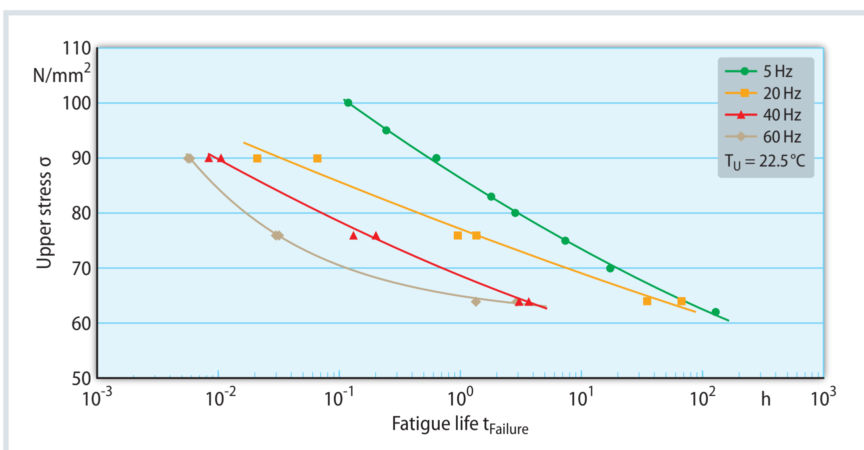

Fig. 4. Influence of the frequency on the time-dependent fatigue life.

Source: IKV; graphic © Hanser

Info

Text

Univ.-Prof. Dr.-Ing. Christian Hopmann holds the Chair of Plastics Processing and is also the head of the IKV.

Hakan Çelik, M.Sc., is conducting research in the field of fatigue and vibroacoustics of short fiber-reinforced plastics; hakan.celik@ikv.rwth-aachen.de

Acknowledgments

The research project 20556 N of the Forschungsvereinigung Kunststoffverarbeitung was sponsored as part of the „industriellen Gemeinschaftsforschung und -entwicklung (IGF)" by the German Bundesministerium für Wirtschaft und Energie (BMWi) due to an enactment of the German Bundestag through the AiF. The investigated material was provided by BASF SE. We would like to extend our thanks to all organizations mentioned.

References & Digital Version

You can find the list of references and a PDF file of the article at ***www.kunststoffe-international.com/archive***

German Version

Read the German version of the article in our magazine ***Kunststoffe*** or at ***www.kunststoffe.de***