DEVELOPMENT OF A MULTISCALE TEST METHOD FOR THE INVESTIGATION OF STRAIN RATE DEPENDENT MATERIAL PROPERTIES OF HIGH-PERFORMANCE FIBERS

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Abstract

For investigations on material behavior at higher strain rates (more than 100 1/s and less than 1000 1/s), no method has yet been described for high-performance fibers due to their low elongation at break. The expected elongation at break determines the maximum distance that can be covered until the test speed has been reached during the acceleration phase. This shortens the time available for accelerating the sample as well as for recording of the forces. It will be shown that, with the help of a rotary drive, it is possible to characterize the material behavior even at higher strain rates. This drive allows the optional adjustment of the testing speed between 10 and 100 m/s, thus, in combination with specimen lengths of 100 to 200 mm, strain rates of 50 to 1000 1/s can be achieved.

1. Introduction

High-performance fibers, such as carbon fibers, form the basis for many fiber-reinforced plastics and concrete applications. In contrast to conventional metal-based constructions and steel-concrete applications, the use of these fibers has a high potential due to the achievable high tensile strength and the simultaneous reduction in total weight. One current field of research is the behavior of the fiber material itself under impact. To understand the behavior of fibers under high strain rates of up to 1000 1/s is essential for the development of more accurate simulation models and design guidelines for high-velocity impact applications. One challenge in testing the high strain rate behavior of carbon and glass fibers is that these high-performance fibers are characterized by a significantly lower strain at break and thus small deformations compared to conventional fibers and steel, resulting in a very short time window in which the breakage occurs. Or in other words, the distance travelled during the acceleration phase of the high-speed test shall be less than the distance derived from the anticipated elongation at break. The resulting time limitations in terms of acceleration and test duration lead to very specific design requirements. For strain rates of more than 1000 1/s, the Split-Hopkinson bar [1, 2] is state of the are, wheras for low strain rates (less than 100 1/s), servo-hydraulic drives are typically used. However, objectives of current research at the Institute of Textile Machinery and High Performance Material Technology include the achievement of an increased speed and strain rate with a rotating disk loading principle. Thus, a multiscale test set-up suitable for stresses ranging from quasi-static up to high-dynamic will be achieved.

This paper presents the necessary theoretical principles and development efforts for the design of a rotary testing system that can characterize high-performance fibers with low elongation at break at high strain rates. As will be shown, the rotating principle has advantages in terms of ease of use and the simplicity of sample preparation, but it requiresspecial design measures: In order to measure forces and energies, normal load cells are an issue above 10 m/s and for small breaking elongations e.g. for carbon and glass fibers.

2. Material and Methods

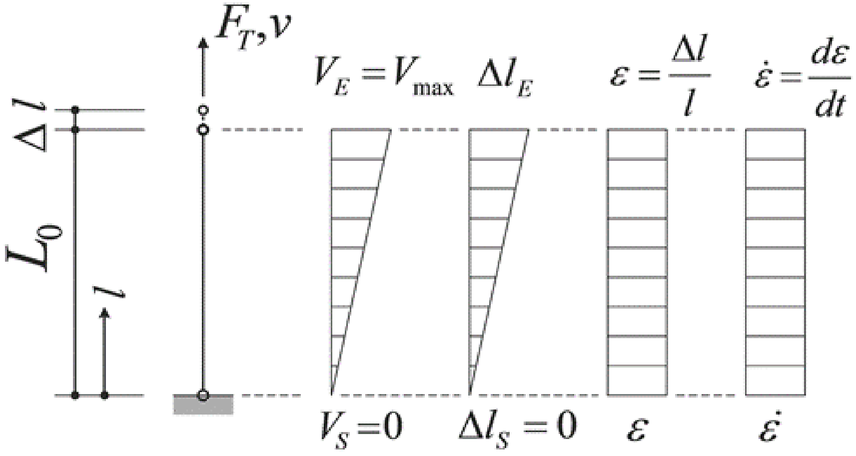

Figure 1. Relation between specimen length, test speed and strain rate.

To design a test stand, it is important to define target parameters. As shown in Figure 1, the strain rate over the sample is constant and therefore only dependent on sample length and test speed. Within the scope of the project, specimens (carbon, glass and aramid fiber bundles) with lengths between 50 and 200 mm and a maximum strain rate (Eq. 1) of 1000 1/s are to be examined, whereby the maximum test speed is limited to 100 m/s for practical considerations.

$$\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t} \tag{1}$$

The defined materials result in a range of potential strain at break between 0.5 to 4 %. Equation 2 can be used to deduce the expected strains and thus relevant trajectory during the test.

$$\varepsilon = \frac{\Delta l}{l} \tag{2}$$

Shorter specimen lengths increase the influence of the clamping, i.e. in the area wher the force is induced into the specimen. Preliminary investigations[4, 5] have shown that clamp mounts cannot hold fiber bundles adequately. By adding a resin coating to the ends of the specimen, clamping fractures and pull-outs could be reduced.

Larger sample lengths reduce the strain rate at the same speed. Conversely, this means that higher strain rates require higher speeds. However, the speed is squared into the centripedal force (Eq. 3).

$$F_Z = m\,\omega^2\,r \tag{3}$$

Additionally, it has to be considered how mass is distributed over the radius of the disc and which internal stresses occur.

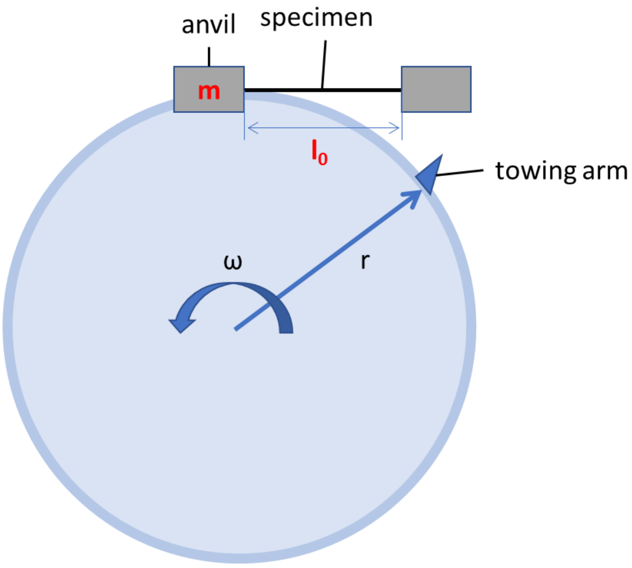

Figure 2. Schematic set-up with washer, anvil, driving arm and specimen.

Figure 2 shows the principle of the test set-up. The rotating disc is mounted horizontally so that additional acceleration forces due to gravity by one revolution of the disc are eliminated. However, this means that the flexible specimens must be held explicitly in position on the side of the anvil. A small preload force prevents the specimen from sagging. This means that the sample is already in position when the disc is accelerated. Once the targeted speed has been reached, the driving arm is extended and accelerates the anvil after the impact.

3. Results and Discussion

Ideally, a tensile test should be performed linearly. Due to the rotary principle in which the driver, that accelerates the loose end of the specimen, describes a circular trajectory, the radius is included in it. This leads to a deviation of the ideal path (Eq. 4, 5) depending on radius and elongation.

$$\varepsilon_{max} \;=\; 2\,\pi\,r\,\alpha \quad für\;\alpha < 5° \tag{4}$$

$$\mathrm{r}\,(1 - \;\cos\alpha) = y_{diff} \tag{5}$$

For a radius of 400 mm and an elongation at break of 8 mm (specimen length 200 mm and 4% elongation at break), an angle of 1.146° and an in-situ displacement of 80 µm are attained.

Another aspect involves minimum and maximum achievable speeds. The upper limit is currently based on the technical implementation of being able to extend the towing arm within one turn, since the sample is already in its fixed position at the start of the test due to the concept.

The lower limit results from the requirement that the speed of the disk itself does not decrease by more than 5%. For this purpose, equations 6 and 7 were used to determine the speed drop due to the test as a function of the mass moment of inertia of the disc and the test speed as shown in Figure 3. A high moment of inertia and a short sample allow lower test speeds without reducing the speed by more than 5%.

$$\frac{J}{2}\omega^2 = \frac{(J + m * r^2)}{2}(\omega - \Delta\omega)^2 + \frac{E * A * \varepsilon^2 * l0}{2} \tag{6}$$

$$\frac{\Delta\omega}{\omega} = 1 - \sqrt{\frac{J\omega^2 - E * A * \varepsilon^2 * l0}{(J + m * r^2)\omega^2}} \tag{7}$$

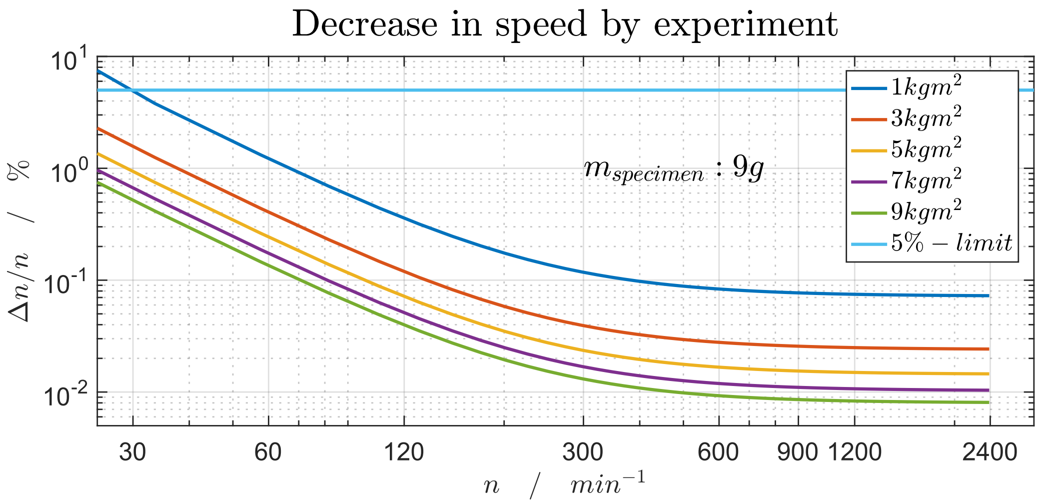

Figure 3. Expected relative speed reduction due to the impact as a function of mass moment of inertia and test speed for a specimen length of 50 mm.

4. Conclusions

The design of the testing machine has proven that tests in the field of high-performance yarns can be carried out even at strain rates of up to 1000 1/sec. The aforementioned explanations show that by taking into account the specific characteristics, i.e.low elongation at break and difficulties with the specimen holder due to the fibre material, an adapted test stand for high-performance fiber materials (carbon, glass and aramid fiber bundles) can be achieved.

This strain rate range covers almost the entire field of shock-stressed components in relation to the resulting fiber stress. The overlapping with servo-hydraulic testing machines in the lower strain rate range also makes it possible to validate the determined material parameters.Therefore, in the future, the model parameters for component design can be specified more precisely, which will also enable lighter, more cost-efficient and safer carbon fiber-reinforced plastic components suitable for vehicles, aviation, robotics and plant construction.

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DFG Deutsche Forschungsgemeinschaft

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