Computer Simulation of Elastomeric Blade and Annular Specimens Testing Taking into Account the Deformation Rate of Their Working Parts

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Abstract. Computer simulation of blade and annular samples made of polymer viscoelastic materials testing has been carried out. Calculations have shown that the rate of material deformation in the working part of the blade specimen can differ significantly from that calculated by the movement of tensile testing machine grips. This is due to the unevenness of the cross-section of blade sample: in the middle (working part) it is constant, and at the ends its area increases. As a result, inhomogeneous stress fields arise in the material, which leads to a variable deformation rate of the specimen working part, even in case when grips move at a constant speed. This effect is not significant at small deformations and a low strain rate and can be ignored in principle. However, in the case of large extensions high speeds, it can seriously distort the test results. According to the authors, the way out of this situation is that, in experiments with viscoelastic polymers, it is better to use annular specimens with the same cross-section along the entire length, rather than blade ones. As shown by computer calculations, in this case, this problem almost completely ceases to exist.

1. Introduction

Elastomeric materials (rubbers) began to be widely used in industry and everyday life only in the 20th century and, despite all the known achievements of scientific and technological progress, they still remain the object of intensive applied and fundamental research. One of the main ways to improve physical and mechanical properties of rubbers is the use of various types of micro and nanofillers, and a great amount of them are known today [1]. First, it is carbon in various allotropic states: carbon black [2, 3] (historically the first and still the most popular filler in the rubber industry); graphene [4]; nanodiamonds [5, 6] and carbon nanotubes [7, 8]. Secondly, it is white soot [9–11] (hydrated silica, the second most common active filler). Thirdly, mineral clay fillers are considered very promising today: montmorillonite, palygorskite, shungite, etc. [12–15].

The input of the above fillers to elastomer can significantly improve mechanical characteristics of the composite (especially strength and deformability). However, the presence in composites of such reinforcing fillers (sometimes they are also called as active fillers) is often accompanied by a significant increase in viscoelastic effects, even for such elastomers, which behave almost like elastic materials in their pure form. For example, natural and styrene butadiene rubbers begin to show their viscoelastic properties already at approximately two to three times elongation [16, 17]. But viscoelasticity depends on the time and rate of deformation. Therefore, it is necessary to have a good understanding when modeling the mechanical behavior of such materials, how stresses change not only from the load magnitude, but also from the rate of its application.

All modern tensile testing machines are quite capable of providing the specified modes of movement of the grips with the required accuracy. However, this does not always mean that the deformation of material will be as required by the tester. This problem usually occurs when using blade samples, especially when they stretch by tens or hundreds of percent. This is due to the unevenness of the cross-section of the blade sample along its length: in the middle (working part) it is constant, and when
approaching the clamps, its area increases significantly. As a result, non-uniform stress fields appear there, which differ from those acting in the working part. This leads to a variable rate of deformation of the working part of the specimen even in the case when the grips move at a constant speed. This effect can significantly distort the results of the experiment.

The main goal of this work was computer simulation of the deformation rate of working parts of blade and annular samples, depending on the speed of movement of grips of tensile testing machine. All calculations were carried out in a three-dimensional setting using the ANSYS finite element computing complex (License ANSYS Academic Research Mechanical and CFD No 106423).

2. The object of study and methods of computer simulation
Two types of samples from the same material were used in computer simulation of viscoelastic behavior of filled elastomers: blade and annular.

The shape and dimensions of blade samples (Figure 1) were in accordance with ISO 527-2 5A standard. The sizes of the working part were 20 mm (length), 2 mm (thickness) and 4 mm (width), i.e. the cross-sectional area was $S_0 = 8 \text{ mm}^2$. The total length of the sample (the distance between the grips in the initial unloaded state) was $L = L_0 = 50 \text{ mm}$, the width near the clamps was 12 mm.

![Figure 1. Blade sample for mechanical testing of filled elastomers](image)

The size of the rings corresponded to the ASTM D 412-2006a "Standard test methods for vulcanized rubber and thermoplastic elastomers — Tension" standard: the outer diameter was 104 mm; inner diameter — 98 mm (i.e. radial thickness — 6 mm); ring width — 2.06 mm. They were put on grips in form of two round rods with a diameter of $d = 5 \text{ mm}$. The length of the working part in the unloaded state $l = l_0$ was also equal 20 mm. Special bounding devices were used to make the annular sample elongated shape (Figure 2). Calculations showed that the resulting stresses in flexible and soft rings after this procedure turned out to be negligible and were not taken into account further.

![Figure 2. Annular specimen for mechanical testing of elastomers, slipped on two round rods and passing through the straightening devices](image)

Two characteristics were used as a measure of deformation: 1) the extension ratio of the whole specimen (along grips) $\lambda_g = L/L_0$; 2) the extension ratio of the working part $\lambda = l/l_0$. $L$ and $L_0$ are distances between the grips at current and initial times, and $l$ and $l_0$ are current and initial lengths of the working part.

The mechanical properties of the simulated samples were set as for SBR-1500 styrene-butadiene rubber filled with particles of carbon black grade N220 (50 phr) — this is a material widely used in modern industry. Equilibrium elastic properties of all samples were set using the Ogden potential [18] for an incompressible medium. Viscous material properties of the samples were described using Prony series.

3. Results discussion

3.1. Monotonic stretching of blade specimens at different speeds
Loading curves of blade specimens stretched with different, but constant within one experiment, speeds of grips movement of tensile machine are presented in Figure 3. Corresponding dependences $d\lambda/dt$ on
The speed of grips varied from $0.35 \text{ min}^{-1}$ to $2.8 \text{ min}^{-1}$, doubling on each subsequent computer experiment.

The graphs show that with an increase in the speed of grips movement, tensile stresses also increase (the material does not have time to relax). The discrepancies between the deformation rates of the working part and the speeds of grips also grow with an increase in $d\lambda_g/dt$ (Figure 4), and the rate of deformation of the working part nonlinearly depends on $\lambda_g$.

3.2. Loading of blade specimens with a stop for relaxation and unloading

Only the stress versus strain dependences can be obtained using mechanical tests for monotonic extension or compression at a constant rate. To study the more complex mechanical behavior of materials both at the experimental [19, 11] and theoretical [20–25] levels, correspondingly, more complex loading paths are required, including repeated loading and unloading of the sample with different amplitudes and periodic stops for relaxation or creep.

Since our work did not aim at a full-fledged study of the physical and mechanical properties of filled polymers, but only to determine the correspondence between the deformation rate of the working part of the sample and the speed of the tensile testing machine grips, we limited ourselves to one test cycle in the form of: Stretching the blade sample to a certain level $\lambda_{max}$, stopping for relaxation and dumping the force load to zero (Figures 5 and 6).
Figure 5. Simulation of loading – unloading at different speeds of grips movement in each test: F/S₀/E₀ versus λₙ.
1 — dλₙ/dt = 0.35 min⁻¹, 2 — 0.7 min⁻¹, 3 — 1.4 min⁻¹, 4 — 2.8 min⁻¹.

Dependences of the specimen working part strain rate on λₙ at different speeds of grips dλₙ/dt are presented in Figure 7.

Figure 6. Simulation of loading – unloading at different speeds of grips movement in each test: F/S₀/E₀ versus time t:
1 — dλₙ/dt = 0.35 min⁻¹, 2 — 0.7 min⁻¹, 3 — 1.4 min⁻¹, 4 — 2.8 min⁻¹.

Figure 7 shows that the higher the strain rate, the stronger the differences between dλₙ/dt and dλ/dt, and the greater is possible distortion of results when determining viscoelastic properties of the material.

In each experiment, the speed of grips movement was constant in absolute value (i.e., both on the forward and on the reverse stroke). All samples relax to approximately the same value, although the maximum stresses achieved during stretching are different for them. They are the larger, the higher is strain rate.

When simulating according to this scheme, it turned out that the complete unloading of the sample (F=0 MPa) occurs before the grips return to their original position, that is, the calculations give the appearance of residual deformations, the values of which enlarge with increasing speed of grips (Figure 5). Such mechanical behavior of the modeled system suggests that this approach does not fully reflect the real situation and needs further refinement. Filled elastomers have a complex internal structure. And it is quite possible that the viscous behavior of the material during unloading and loading is different. Residual deformations in experiments with filled elastomers are observed quite often, but whether they are associated with insufficient relaxation time or irreversible changes in the structure, that is, plastic flow was not considered in this work.
Figure 7. Dependences of $d\lambda_g/dt$ on different $d\lambda_g/dt$ for the loading curves from Figure 5.

(a) $-d\lambda_g/dt = 0.35 \text{ min}^{-1}$, (b) $-0.7 \text{ min}^{-1}$, (c) $-1.4 \text{ min}^{-1}$, (d) $-2.8 \text{ min}^{-1}$

It should be noted that, in addition to viscoelasticity, the difference in velocities can be influenced by other effects inherent in the mechanical behavior of filled elastomers, for example, the Mullins softening effect [26], which was not considered in this work.

3.3. Annular elastomeric specimens

Computer tests, similar to those described earlier, were carried out to check the annular specimens from the point of maintaining a given rate of deformation. The relationship between the rates of strain of the specimen working part and the grips movement was investigated.

As an example, Figure 8 shows dependences of the deformation rate of the working part of annular viscoelastic specimen $d\lambda/dt$ on the extension ratio $\lambda_g$, when tested for simple uniaxial tension at different speeds of grips in each experiment. As expected, $d\lambda/dt$ and $d\lambda_g/dt$ practically coincided. The same picture was observed for complex loading trajectories.
Summary

It has been shown by computer simulation methods that the rate of deformation of the working part of viscoelastic blade specimens can change significantly during loading even at a constant speed of movement of tensile testing machine grips. This effect is not significant at small deformations and a low strain rate and can be ignored in principle. However, in the case of large extensions high speeds, it can seriously distort the test results. The way out of this situation is that in experiments on the study of the viscoelastic properties of materials, it is better to use not bladed, but annular samples.

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Figure 8. Dependences of deformation rates of the annular specimen working part on \( \lambda_g \) under simple tension at various speeds of grips:

1 — \( \frac{d\lambda_g}{dt} = 0.35 \text{ min}^{-1} \), 2 — 0.7 \text{ min}^{-1} ,
3 — 1.4 \text{ min}^{-1} , 4 — 2.8 \text{ min}^{-1}
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