The research on the influence of temperature on the properties of synthetic fibres for load-handling devices

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Abstract. This article presents the results of experimental studies aimed at analyzing the impact of various temperature conditions on the performance characteristics of synthetic fibres and threads, widely used in lifting devices in construction. Not only the positive aspects of using these materials are discussed, but also the design features of synthetic load-bearing devices. In addition, a classification of materials used in the lifting industry is carried out, with an emphasis on polymer complex fibres. The physicomechanical and physicochemical properties of these materials are studied at various temperature conditions. To achieve these goals, research was carried out using modern physical-mechanical, physical-chemical, mathematical-statistical methods, methods of mathematical modelling, experimental planning, as well as methods of computer science and computational mathematics. These methods ensured the reliability and accuracy of the results obtained, which allows us to draw conclusions that have practical significance for the design and operation of lifting systems in a variety of climatic conditions.

1 Introduction

World experience in the use of synthetic textile and round-strand flexible load-handling devices has confirmed their extreme reliability when operating in the most difficult conditions, when lifting and unloading a variety of cargo, including in construction. The production of textile slings begins with the production of synthetic fibres and threads, which, in addition to slings, have many other practical applications [1]. Multifilament and para-aramid fibres and threads based on synthetic high-molecular-weight (SHMW) materials are widely used as raw materials for the production of tapes and ropes.

Among synthetic fibres, production is developing most dynamically polypropylene (PP) fibres and threads, which have found wide acceptance, both for manufacturers of technical products and in the production of consumer goods. This is explained by the availability of raw materials, the simplicity of the technology for producing fibres, and the fairly high-performance characteristics of products made based on PP fibres and threads [2].

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The tasks that are solved in this work are to identify the relationship between the characteristics of deformation properties and the molecular processes occurring in polyolefin threads. Particular attention is paid to the study of the residual component of deformation, as one of the main characteristics of the dimensional stability of materials after mechanical loading. The influence of elevated temperatures and moisture on the characteristics of the mechanical properties of synthetic threads and fibres of the polyamide and polyolefin series is considered. Therefore, let us dwell on some aspects of this problem. It is especially important to study the influence of temperature effects on the characteristics of the mechanical properties of aramid fibres and threads, which are associated with their use at high temperatures. The main temperature characteristics of fibres of the amide and olefin series are presented in the table 1 [3,4].

It should be noted that the glass transition temperature of rigid chain polymers differs from the traditional glass transition temperature of flexible chain polymers. As shown by the authors of [5], upon reaching a certain temperature, which can be conventionally designated as the glass transition temperature, partial mobility occurs due to limited torsional vibrations of elementary units or, simultaneously, longitudinal wave vibrations of the macromolecule as a whole. Segmental mobility, typical of flexible-chain polymers, is practically absent in rigid-chain polymers. However, limited mobility turns out to be sufficient for a phase transition from the initial nonequilibrium amorphous state to a more equilibrium liquid crystalline state. The defrosting temperature of limited mobility is conventionally called the glass transition temperature.

The heat resistance of aramid fibres depends both on the chemical structure and on the technology for their production. Typically, the strength of these fibres decreases monotonically as the temperature increases. For most aramid fibres, at 300 °C the strength is 50–55% of the original value. Works [7,8] are devoted to studying the influence of thermal ageing on the deformation properties of aramid fibres and threads.

1.1 Materials and methods

Scientists began to study the use of synthetic textile products in engineering and technology in the middle of the last century, that is, from the time when the high strength of synthetic materials was discovered by molecular chemistry. In the United States of America, in developed countries of Europe and the Russian Federation, research is being conducted to study the use of high-strength textile synthetic materials in various industries.

Scientists, including A.K. Schreiber and Ya.G. Gordin, studied the problems of using non-woven tapes and ropes (NTTA) in the production and transportation of various products, during their loading, construction, installation and rescue operations. In the 1990s, with the help of NTTA, various lifting devices began to be developed.

The deformation properties of materials were studied in detail by scientists A.P. Aleksandrov, N.H. Arutyunyan, A.R. Ryanitsyn, Kh.A. Rakhmatullin, and are based on the fundamental theory of elastic viscosity.

Relaxation, the macrostructure of polymer fibres, their hardness, fragility, fatigue, elongation and creep, elastic viscosity, physicochemical resistance and deformation properties under working conditions have been studied in detail by such scientists as A.A. Askadsky, G.M. Bartenev, A. Y. Goldman, I. V. Abramov, O. E. Kalanchuk, V. A. Berestnev, L. S. Gerasimova, B. Wunderlich, A. G. Makarov, A. M. Stalevich, K. E. Perepelkin, Yu.N. Rabotnov, E.S. Tsobkallo.
2 Materials and methods

To date, the processes characterizing structural changes for para-aromatic fibres at high temperatures have been quite well studied and generalized [9]. Less studied is the change in the mechanical properties of aramid fibres at temperatures below the glass transition temperature. The data presented in the literature relate mainly to strength characteristics, creep and relaxation processes and do not address the problem of studying residual deformations [9]. The most important factor influencing the characteristics of the mechanical properties of hydrophilic fibres, which include all amide fibres, is moisture. Moisture absorption is typical for polymers in which intermolecular interaction is realized through hydrogen bonds, since water molecules are prone to form hydrogen bonds, both with water molecules and with polar groups. Moisture sorption occurs mainly in amorphous regions of the structure. Aromatic polyamide threads have an amorphous-crystalline (Teflon, Kevlar, phenylene, Nomex) or mesomorphic structure (SHMW, Armos) and contain polar groups (NH, CO) that can sorb water. It was established in [9] that mesomorphic regions are accessible to moisture, and the interaction of water molecules with certain sections of the chains can lead to the amorphization of the structure. It is assumed that these sites are amide groups, and the amorphization effect is explained by the destruction of hydrogen bonds formed by these groups.

Table 1. Temperature characteristics of the studied fibres of the polyamide and polyolefin series

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Temperature, ◦C</th>
<th>Decompositions</th>
<th>Operation (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar</td>
<td>345–360</td>
<td>450–550</td>
<td>250–270</td>
</tr>
<tr>
<td>Terlon</td>
<td>345–360</td>
<td>450–550</td>
<td>250–270</td>
</tr>
<tr>
<td>SHMW</td>
<td>270–300</td>
<td>500–550</td>
<td>300–330</td>
</tr>
<tr>
<td>Armos</td>
<td>270–300</td>
<td>500–550</td>
<td>300–330</td>
</tr>
<tr>
<td>Nomex</td>
<td>275–300</td>
<td>370–400</td>
<td>250–300</td>
</tr>
<tr>
<td>Phenylene</td>
<td>275–300</td>
<td>370–400</td>
<td>250–300</td>
</tr>
<tr>
<td>Nylon, nylon 66</td>
<td>40–70</td>
<td>300–320</td>
<td>215 (melting)</td>
</tr>
<tr>
<td>Polypropylene (isotactic)</td>
<td>(–12–20)</td>
<td>350–380</td>
<td>170–180 (melting)</td>
</tr>
</tbody>
</table>

Work [10] provides data on the interaction of SHMW fibres with water vapour. There are three stages of this effect: at the thread moisture content of 0–2%, sorption is carried out by free amide groups; at a humidity of 2–3%, hydrogen bonds between adjacent polymer chains are broken, which leads to the formation of hydrogen bridges with the participation of water molecules. A further increase in humidity leads to a weakening of intermolecular water-polymer bonds and an increase in the mobility of molecules. Analysis of the NMR spectra of SHMW filaments carried out in [11, 12] confirms the assumption of the formation of hydrogen bridges. According to works [13, 14], under certain conditions, moisture can behave as a plasticizer; however, in rigid-chain polymers, which themselves are prone to ordering processes, an anti-plasticization effect can also be observed. For traditional amide series yarns (nylon, nylon), the issues of the influence of moisture and hydrogen bonds on the deformation and strength properties of fibres and threads are also of great interest. As shown in [15], the presence or absence of moisture, and the number and type of hydrogen bonds significantly affect the properties of these fibres. The issue of the interaction of water with nylon is discussed in some detail in [16].

It has been shown that water molecules form double hydrogen bonds between two carbonyl groups - strongly bound water. Water molecules can also form hydrogen bonds between carbonyl groups and the hydrogen atoms of amide groups - weakly bound water.
The object of the study was industrially produced highly oriented polypropylene thread (PP-1). Studies of mechanical properties and structural processes were carried out at temperatures $T = 20$, 50, 80, and 100 °C, which are above the glass transition temperature and significantly below the melting temperature.

It has been shown that a significant change in the tensile speed (from 0.1 to 500 mm/min) does not cause a significant change in the appearance of these curves - the change in strain and stress values in the specified speed range was no more than 5%. Thus, in a certain range of deformation rates, the tensile curve can be considered a fairly stable characteristic of the mechanical properties of this thread.

Analysis of the shape of the $\sigma(\varepsilon)$ curves allows us to note that the tensile diagrams of the PP thread consist of two sections, the boundary between which is located near $\varepsilon \approx 4$–5%. For a more accurate analysis of the shape of these curves, the values of the current (tangent, tangential) $E(\varepsilon)$ module were calculated, obtained by differentiating the diagram, i.e. $E(\varepsilon) = \frac{\partial \sigma(\varepsilon)}{\partial \varepsilon}$.

Note that special attention will be paid to the $E(\varepsilon)$ dependences in the work, as one of the important deformation characteristics that allows one to analyse the shape of the stress diagrams constructed for the $E(\varepsilon)$ dependences for PP–1. On the $E(\varepsilon)$ curve, two characteristic areas can be distinguished: the first is an unextended initial area ($0 < \varepsilon < 4\%$), associated with an increase in the current module; the second is extended, including almost the entire range of deformation (from $\varepsilon > 4\%$ and up to discontinuous values of deformation) the region of the drop of the current modulus [17].

Let us pay attention to the fact that the values of the boundary deformation ($\varepsilon_r$), corresponding to the maximum in the $E(\varepsilon)$ dependences and determining the transition from one section to another ($\varepsilon_r \approx 4$–5.5%), are practically independent of temperature. An increase in temperature leads to only a slight shift of this maximum to the region of large deformations [18].

### 3 Results and discussion

The processes of creep and elastic recovery of the PP-1 thread were studied in a wide range of loads (from low to pre-rupture) at temperatures of 20, 50, 80, and 100 °C. The recovery processes took place with the complete unloading of the samples. The creep and elastic recovery time was 10 min. Longer (over 2 hours) experiments on elastic recovery were also carried out. It has been shown that the speed of the recovery process drops significantly over time, so we can assume that most of this process takes place in a time of 10 minutes. The families of creep and elastic recovery curves for the PP-1 film thread are presented in Fig. 1–4 in a semi-logarithmic coordinate system. The intensity of the creep process significantly depends on the magnitude of the applied load, i.e. an increase in the rate of creep is observed at certain stress values.

Let us turn to the consideration of the recovery deformation process of the PP film thread, which is shown in Fig. 1–4 is presented on the right side. It should be noted that the process of elastic recovery also occurs “unevenly”, i.e. at low loads during creep and then unloading, an almost complete restoration of the dimensions of the film thread is observed [19,20,21].

In Fig. 1 shown are the families of creep (I) and elastic recovery (II) curves for polypropylene thread (PP-1), obtained at $T = 20$ °C and different voltage values.
Values of σ, MPa: 24(1); 40(2); 79(3); 95(4); 119(5); 134(6); 159(7); 187(8); 198(9); 214(10); 240(11); 262(12); 278(13); 294(14); 315(15).

**Fig. 1.** Families of creep (I) and elastic recovery (II) curves for polypropylene thread (PP-1), obtained at T = 20 °C and various stress values

Values of σ, MPa: 24(1); 40(2); 56(3); 63(4); 79(5); 95(6); 100(7).

**Fig. 2.** Families of creep (I) and elastic recovery (II) curves for polypropylene thread (PP-1), obtained at T = 50 °C and various stress values

Values of σ, MPa: 24(1); 40(2); 56(3); 63(4); 79(5); 95(6); 100(7); 119(8); 134(9); 154(10).

**Fig. 3.** Families of creep (I) and elastic recovery (II) curves for polypropylene thread (PP-1), obtained at T = 80 °C and various stress values

Values of σ, MPa: 24(1); 40(2); 56(3); 63(4); 79(5); 95(6); 100(7).
An increase in load leads to the appearance of fairly large residual deformations. Using families of creep–recovery curves, the dependences \( \varepsilon_{\text{res}}(\sigma) \), were obtained, which determine the accumulation of the irreversible component of deformation depending on the applied stress (Fig. 4). In these dependencies, the deformations obtained at the end of the recovery process, which lasted 10 minutes, were considered residual. Similar dependencies were obtained for a recovery process duration of 2 hours. A comparison of the dependences \( \varepsilon_{\text{res}}(\sigma) \) obtained at different recovery times showed that increasing the duration of this process leads to only a slight decrease in the values of the residual component and does not change the nature of this dependence. At all temperatures, two sections are observed in the \( \varepsilon_{\text{res}}(\sigma) \) dependences. In the first section, residual deformations are small. Exceeding certain (for each temperature) limit values of stress \( \sigma_{l} \) causes a significant increase in residual deformations:

- \( T = 20 \, ^\circ C \): \( \sigma_{l} \approx 120 \, \text{MPa} \);
- \( T = 50 \, ^\circ C \): \( \sigma_{l} \approx 60 \, \text{MPa} \);
- \( T = 80 \, ^\circ C \): \( \sigma_{l} \approx 35 \, \text{MPa} \);
- \( T = 100 \, ^\circ C \): \( \sigma_{l} \approx 22 \, \text{MPa} \).

The dependences \( \varepsilon_{\text{res}}(\sigma) \), obtained for different temperatures, make it possible to determine not only \( \sigma_{r} \), but also those values of residual strain (\( \varepsilon_{\text{res}}^{r} \)), the excess of which leads to intensive growth of the irreversible component [22,23]. So, even fairly small loads cause irreversible processes in the oriented PP, which is confirmed by the intensive growth of the residual component. To establish the relationship between the values of stress and strain during the creep process, isochronous dependences \( \sigma(\varepsilon_{10}) \) were used, obtained for different temperatures from a family of creep curves. From the isochronous dependencies, the boundary values of the creep strain \( \sigma_{r} \) were determined, corresponding to the stress values \( \sigma_{r} \).

The comparisons showed that all values of \( \sigma_{r} \) correspond to a close value of \( \varepsilon_{r} \approx 4\% \).

### 4 Conclusion

Thus, the onset of intensive growth of residual deformations is determined by a constant elongation strain value for a given material, practically independent of temperature. To confirm this conclusion, the dependence \( \varepsilon_{\text{res}}(\varepsilon_{3}) \) was constructed, characterizing the relationship between the values of residual strain and the strain specified during the creep process. This dependence has a transition in the region \( \varepsilon \approx 4+5\% \), which corresponds to the value \( \varepsilon_{r} \).

The dependence \( \varepsilon_{\text{res}}(\varepsilon_{3}) \) is general for all studied temperatures, i.e. for an oriented PP, residual deformations are determined by given elongations.
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