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STRESS AND TEMPERATURE CHANGES OF POLYMER WOVEN BELTS SUBJECTED TO MECHANICAL LOADING

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The experimental results obtained during low-cyclic tensile deformation of woven polyamide belts were presented. The temperature and mechanical characteristics of tension, low-cyclic loading, unloading and stress relaxation processes were found. The temperature changes accompanying the woven belt deformation turned out to differ from those, which were found for the sheet polyamide solid specimens. Such temperature results were caused both by the effects of the material as well as by the effects of the fibrous belt structure. The maximal temperature increments observed during subsequent cycles of loading reached 10 K. The cycling test actually did not affect the stress-strain characteristics of the belts, so it can be concluded that the used belt structure ensures their safe application for various cyclic loadings.

Key words: tensile deformation, low-cyclic tests, woven belt, polyamide, temperature changes.

1. Introduction

Polymers represent an important class of materials, which have now become indispensable in modern life and industry. Topics of the polymers behavior at various kinds of investigations have been one of considerable interest during the last decade. During the last few years, a great number of papers has been published on both the experimental and theoretical aspects of deformation mechanisms in crystalline polymers, usually applied in modern life. Nevertheless, the understanding of the basic mechanisms of the elastic and plastic deformation of these materials has been a subject of intense research for the last years. The variety of the microscopic structure and morphology influences the differences in their properties. Furthermore, all kinds of loading leading to the material deformation modify the temperature fields of the material subjected to testing. Conversely, the temperature variations influence the mechanical material behavior. Such an interaction between stress, strain and temperature fields, called thermomechanical coupling, can be significant for polymers, since both their melting temperature and heat capacity are rather low [1, 2, 3].

Deformation of solid polymers in the initial, elastic range is accompanied by temperature changes, up to 2 K [1, 2]. The temperature changes of the solid subjected to loading in this reversible stage was described by the Kelvin law as a linear function of the first invariant of stress tensor: $\Delta T = -k\Delta\sigma_{ii}$. Thus, in the elastic range of deformation, the temperature decreases during tension, increases during compression and does not change during shear or torsion [4]. The plastic deformation of a solid is always accompanied by increase in temperature, caused by conversion of a significant part of the supplied mechanical energy into heat [3, 5, 8].

One of the effective and quite efficient, however still not too popular methods of investigation of the mechanical properties of polymers, according to their application, is the stress analysis, based on detection of the temperature changes caused by the stress changes [3, 5, 7]. One of the useful tools for such an approach is an infrared camera. The goal of the present study is investigation of the thermomechanical behavior of polymer product – a woven polyamide belt, applied in aircraft transport, subjected to low-cyclic tension loadings and stress-relaxation tests.

2. Experimental details

The investigations were carried out on the belts of polyamide fibers, applied in aircraft transport. A sketch of such a belt is shown in Fig. 1; its macroscopic structure in Fig. 2. Total belt length was equal to 540 mm; the measurement part – 150 mm, the width – 45 mm, the thickness – 4 mm. The average fiber diameter was about 30 μm; each thread consists of about 147 fibers. The belts were weaved with duplex interlace (see Fig. 2). Detailed structure of the polyamide woven belt was described in [6].

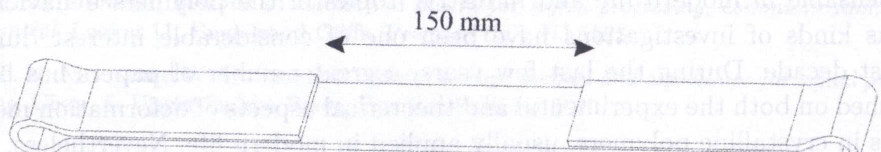

FIG. 1. Outline of polyamide woven belt.

The belt was fitted in especially designed grips and subjected to uni-axial tension tests. All the investigations were carried out at room conditions, with constant strain rate. These rates should be high enough in order to provide temperature measurements measurable by the thermovision camera. Elongation of the belt subjected to loading was measured with an extensometer of the gauge length 25 mm + 50%. Especial design of the grips allowed for increasing of the measurement base up to 50 mm. A photograph of the measurement set up is shown in Fig. 3.

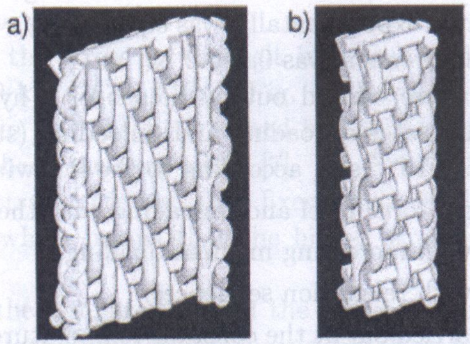

FIG. 2. Macroscopic structure of polyamide woven belt: a) cross-section parallel to the belt surface, b) cross-section perpendicular to the belt surface [6].

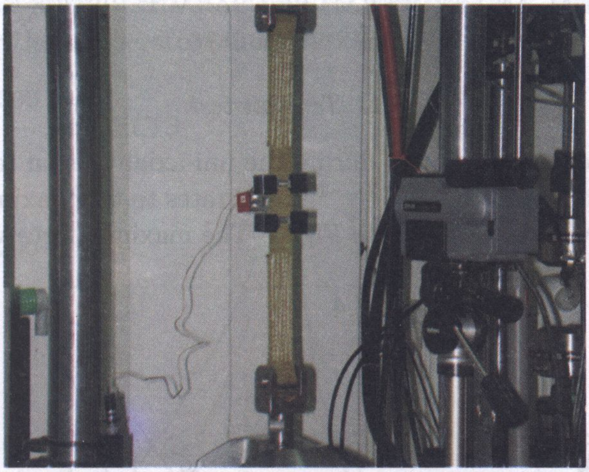

FIG. 3. Photograph of the measurement set-up designed for investigation of polyamide woven belt.

The force, time, elongation, as well as distribution of the infrared radiation from the specimen surface were continuously registered during the belt loading. The distribution of the infrared radiation was registered by means of infrared camera, interconnected with a computer system of the data acquisition and conversion, which allowed for digital registration of the obtained images with a frequency of 50 Hz. The computer enables to register, store and reconstruct the obtained mechanical and temperature data. In this way, various temperature data can be presented as a function of various mechanical parameters, as required.

The temperature on the belt surface was indicated as the average value on the specimen surface 25 mm × 20 mm, taken from the central part of the belt between the grips, where the extensometer was fitted (Fig. 3). The emissivity of the belt surface, indicated experimentally, was equal to $\varepsilon_m = 0.81$. The accuracy of the temperature measurement was 0.1–0.2 K.

The investigations were carried out by means of a hydraulic testing machine, with the constant rates of loading and unloading (strain rate), equal to 6.5×10^{-3} s^{-1} and 3.5×10^{-2} s^{-1}, according to the following procedure:

- loading to a proper force level and unloading with the same strain rate,
- low-cycling test with increasing maximal loading,
- low-cycling test with relaxation sequences.

All the tests were carried out at the constant temperature (about 295 K) and the constant air humidity (about 50%). All the belts were stored before testing in the same conditions.

3. Mechanical and temperature characteristics of polyamide woven belts

3.1. *Tension test*

Stress-strain curves, obtained during the uni-axial tension tests, carried out with 6.5×10^{-3} s^{-1} and 3.5×10^{-2} s^{-1} strain rates to the maximal loading level of 40 kN (263.2 MPa), are shown in Fig. 4. The maximal force value 40 kN was

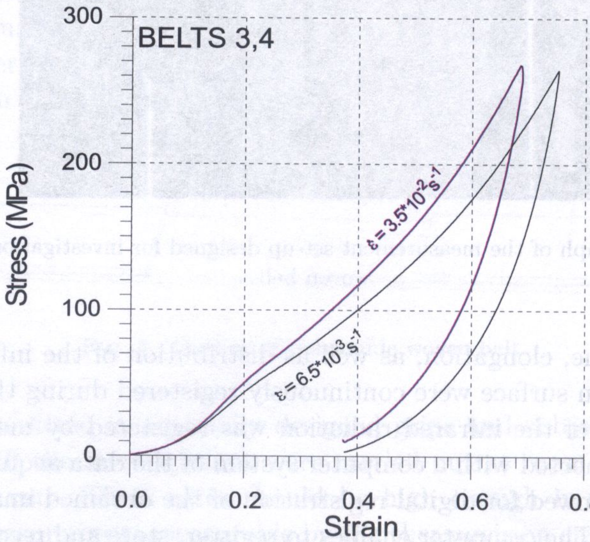

FIG. 4. Stress-strain curves, obtained during uni-axial tension tests of polyamide woven belt for two different strain rates: 6.5×10^{-3} s^{-1} and 3.5×10^{-2} s^{-1}.

chosen in referring to the belts strength. At the higher force level, delamination of grip parts of the belt was observed (Fig. 1), namely rupture of the fibers and the glue joining the belt parts. These effects disturbed the measurement results and their proper interpretation.

During loading, the stress in the belt increased almost monotonically, up to the load limit 40 kN (263.2 MPa) (Fig. 4). During unloading, a significant decrease in the strain was observed caused by the material viscosity, similar to that registered for shape memory alloys [7].

For the higher strain rate test, the fixed stress level was obtained for the lower strain value, which means that the higher strain rate, the higher stress level is achieved.

An example of the temperature and the stress vs. time curves is shown in Fig. 5. In the initial stage of tension the temperature changes are very small. Probably it was caused by accommodation of the belt structure to the direction of the applied loading – the stress increment in the measurement range was rather small and the friction effects might cause the temperature increase. Next, a significant elongation of the measurement belt part was observed which was accompanied by the temperature increase, up to 6 K.

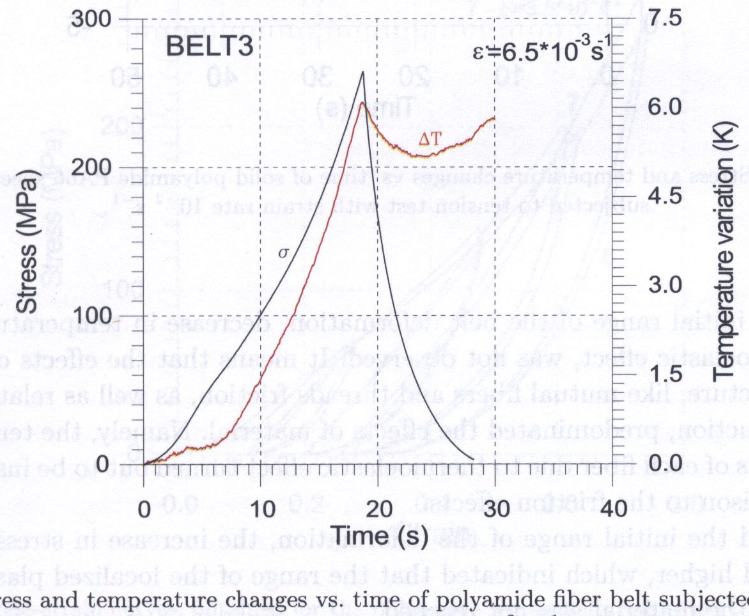

FIG. 5. Stress and temperature changes vs. time of polyamide fiber belt subjected to tension test with strain rate 6.5×10^{-3} s^{-1}.

During unloading, a decrease in temperature was observed, followed by the temperature increase, registered also when the unloading process was completed (null loading level).

The run of the stress-strain curve, as well as the run of the stress and the temperature vs. time curves, obtained for the woven belts, are quite different from those found for the sheet polyamide specimens, subjected to similar testing (Fig. 6), [2, 8].

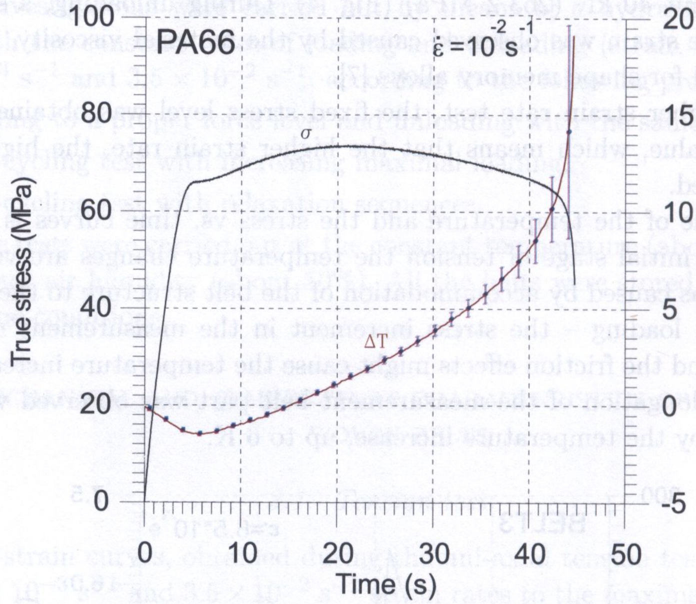

FIG. 6. Stress and temperature changes vs. time of solid polyamide PA66 sheet sample subjected to tension test with strain rate 10^{-2} s^{-1}.

In the initial range of the belt deformation, decrease in temperature, called the thermoelastic effect, was not observed. It means that the effects of the material structure, like mutual fibers and threads friction, as well as related to this heat production, predominated the effects of material. Namely, the temperature decrements of each fiber due to thermoelastic effect turned out to be insignificant in comparison to the friction effects.

Beyond the initial range of the deformation, the increase in stress was still higher and higher, which indicated that the range of the localized plastic deformation of the material was not reached.

The stress-strain curve for the sheet polyamide specimen shows a typical run (Fig. 6). It was started from a reversible elastic deformation, accompanied by the drop in temperature up to minus 2 K, followed by plastic deformation, characterized by the temperature increase up to 13 K for this strain rate and finally, rapid temperature increase, related to the specimen necking and damage.

3.2. *Low cycling tests*

The woven polyamide belts are subjected to subsequent loading and unloading cycles during their practical application. In order to study their mechanical behavior and the temperature changes, as well as to predict their material reliability, investigations of the mechanical and the temperature characteristics during low cycling tensile tests with two different strain rates were performed.

The testing was carried out according to the following procedure:

- loading to 10 kN (65.8 MPa), unloading to 0,
- loading to 20 kN (131.6 MPa), unloading to 0,
- loading to 30 kN (197.4 MPa), unloading to 0,
- loading to 40 KN (263.2 MPa), unloading to 0.

Two strain rates were applied, the same as those during the former tests: $6.5 \times 10^{-3}\ \mathrm{s}^{-1}$ and $3.5 \times 10^{-2}\ \mathrm{s}^{-1}$. The obtained stress-strain curves are shown in Fig. 7.

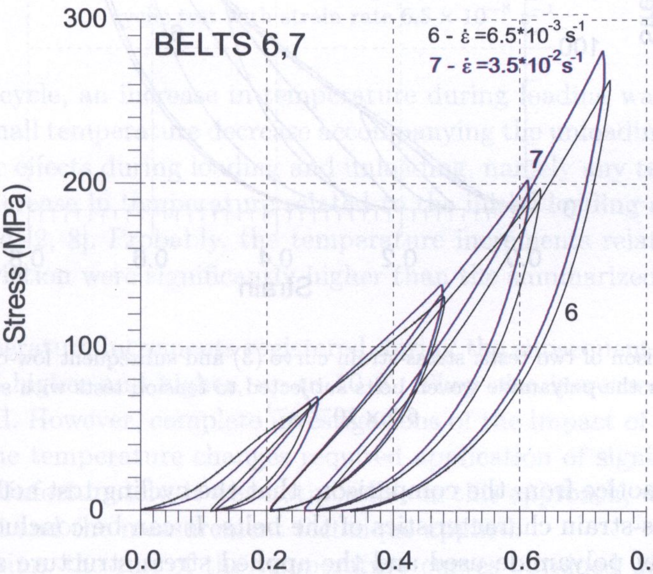

FIG. 7. Stress-strain curves, obtained for the polyamide woven belts subjected to low-cyclic tests with two different strain rates: $6.5 \times 10^{-3}\ \mathrm{s}^{-1}$ and $3.5 \times 10^{-2}\ \mathrm{s}^{-1}$.

Similarly, like during the uni-axial tension tests, the higher strain rate, the higher loading value was obtained for the same strain value applied. During unloading, for the subsequent number of cycles, the strain becomes proportionally smaller. This effect was similar to those, which were observed for shape memory alloys [9]. Such a viscosity effect is especially significant for cycles in which higher maximal loading was used.

In order to estimate the influence of the subsequent loading and unloading processes on the stress-strain characteristics, the stress-strain curves obtained with the same strain rates for the belts subjected to uni-axial tension test (belt 3) and uni-axial subsequent low-cyclic tests (belt 6) were compared (Fig. 8).

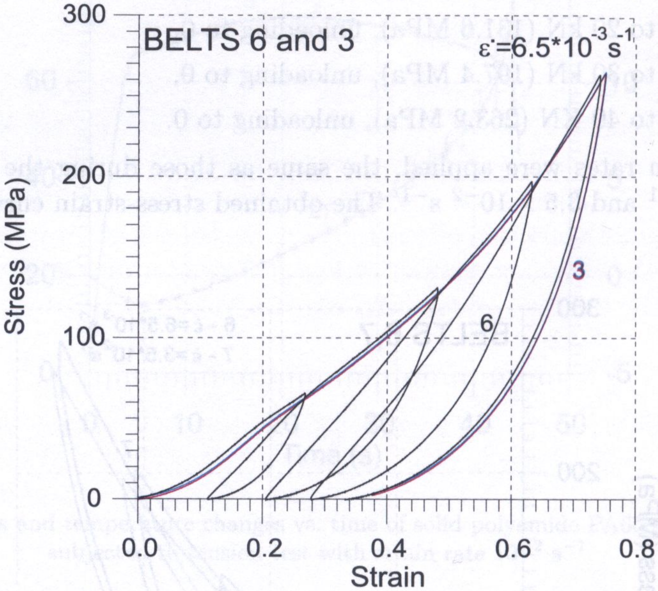

FIG. 8. Comparison of two tests: stress-strain curve (3) and subsequent low-cyclic tests (6), obtained for the polyamide woven belts subjected to tension tests with strain rate 6.5×10^{-3} s^{-1}.

One could notice from the comparison, that the cycling test actually did not affect the stress-strain characteristics of the belts. It can be concluded therefore that the kind of polyamide used and the applied stress structure allow for safe application of the woven polyamide belts in aviation transport for such kinds of loadings.

According to the thermomechanical aspect of the study, as it was mentioned above, the main task was to determine the temperature changes of the belts subjected to loading cycles and to find its influence on the mechanical characteristics, namely investigation of the thermomechanical coupling effects. An example of the temperature and the stress characteristics of the polyamide belts subjected to low cyclic subsequent test is shown in Fig. 9.

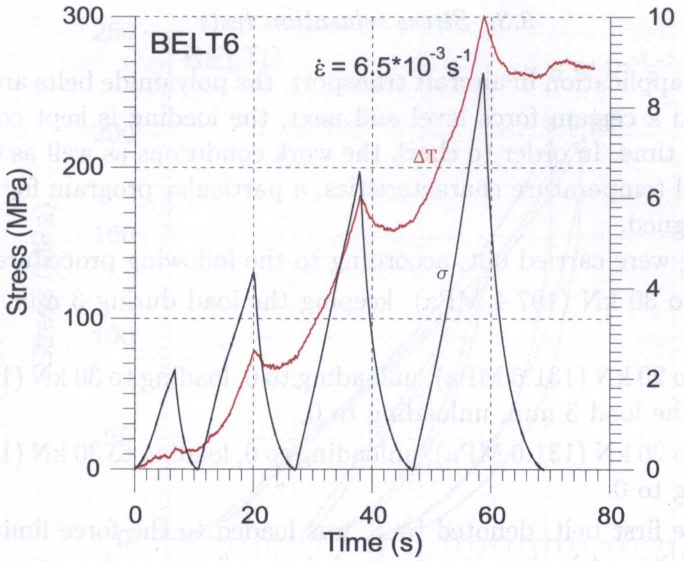

FIG. 9. Stress and temperature curves of polyamide woven belt subjected to subsequent cyclic test with strain rate 6.5×10^{-3} s^{-1}

For each cycle, an increase in temperature during loading was observed followed by a small temperature decrease accompanying the unloading process. Any thermoelastic effects during loading and unloading, namely any temperature decrease and increase in temperature related to the initial loading and unloading, were observed [2, 8]. Probably, the temperature increments related to the mutual woven friction were significantly higher than the summarized thermoelastic effects.

The temperature increments registered during the subsequent cycles of loading were still higher and higher, up to 10 K. They also increased as the strain rate increased. However, complete investigations of the impact of the strain rate applied on the temperature changes required application of significantly higher strain rates. Unfortunately, it was not possible in this approach, with the testing machine used and the measurement technique applied.

Summarizing, the run of the temperature curves obtained during the belts investigations indicates that the temperature increments are mainly caused by mutual interaction of the threads and fibers – the elements of the polyamide belt structures, as well as the threads deformation, observed for higher loadings.

The temperature changes observed for the applied number of cycles of deformation are not too high, in comparison to the sheet solid specimens. However, for a higher number of cycles and higher amplitude value, the temperature changes can be much higher and may influence significantly both the belt elongation value as well as the belt strength.

3.3. *Stress relaxation tests*

During the application in aircraft transport, the polyamide belts are also used to be loaded to a certain force level and next, the loading is kept constant for some period of time. In order to check the work conditions as well as to find the mechanical and temperature characteristics, a particular program for relaxation tests were designed.

The testing were carried out, according to the following procedures:

1. loading to 30 kN (197.4 MPa), keeping the load during 3 min, unloading to 0,
2. loading to 20 kN (131.6 MPa), unloading to 0, loading to 30 kN (197.4 MPa), keeping the load 3 min, unloading to 0,
3. loading to 20 kN (131.6 MPa), unloading to 0, loading to 30 kN (197.4 MPa), unloading to 0.

Namely, the first belt, denoted by 8, was loaded to the force limit of 30 kN (197.4 MPa), followed by keeping the load during 3 min and next, unloaded to null. The second belt, denoted by 9, was loaded to 20 kN (131.6 MPa), unloaded to 0, loaded to 30 kN (197.4 MPa), which was followed by keeping the load during 3 min at the obtained strain level and next, unloaded. The third belt, denoted by 10, was subjected to 2 cycles of the loading and unloading; up to 20 kN (131.6 MPa) and 30 kN (197.4 MPa), without any relaxation sequences. The strain rate for all the tests was equal to 6.5×10^{-3} $s^{-1}$and it was keeping constant during the loading and unloading, like for the former tests.

In this way, it was possible to estimate the impact of stress relaxation process on the mechanical and temperature behavior of the belts subjected to further loading.

The results, namely the stress-strain curves obtained for three approaches described above, are shown in Fig. 10. The discrepancies between the curves observed during the unloading resulted from statistic scattering – slight differences in the particular belt structure.

In order to compare in more details the mechanical and the temperature characteristics obtained during the subsequent cycles of loading, with and without the stress relaxation, the stress and the temperature curves were presented also as a function of time (Figs. 11, 12, 13).

During the initial stage of the relaxation test, both in the first cycle of loading (Fig. 11) as well as in the second one (Fig. 12), a rapid decrease in stress was observed, followed by the smooth one. The sudden stress decrease was accompanied by a significant increase in temperature, followed by the temperature decrease resulting from the heat exchange with the surroundings. During unloading, a drop in temperature registered at the beginning followed by an increase in temperature up to 1 K was observed.

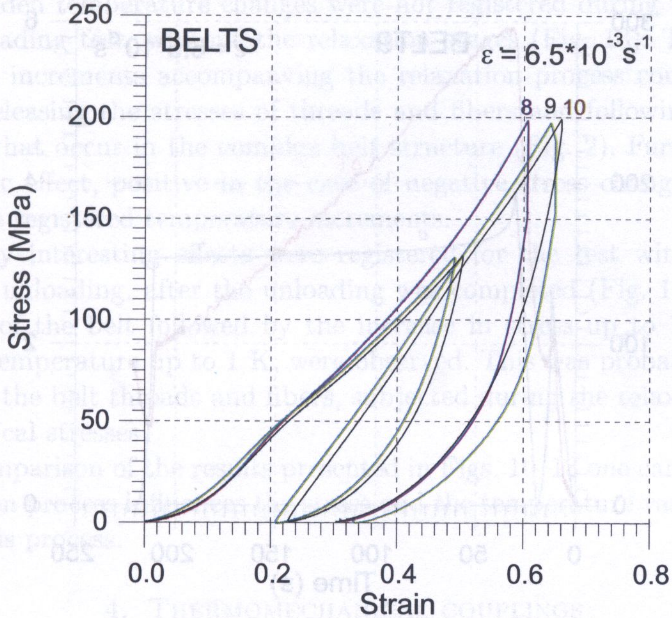

FIG. 10. Stress-strain curves obtained during relaxation tests of woven polyamide belts; 8, 9, 10 denote the test numbers.

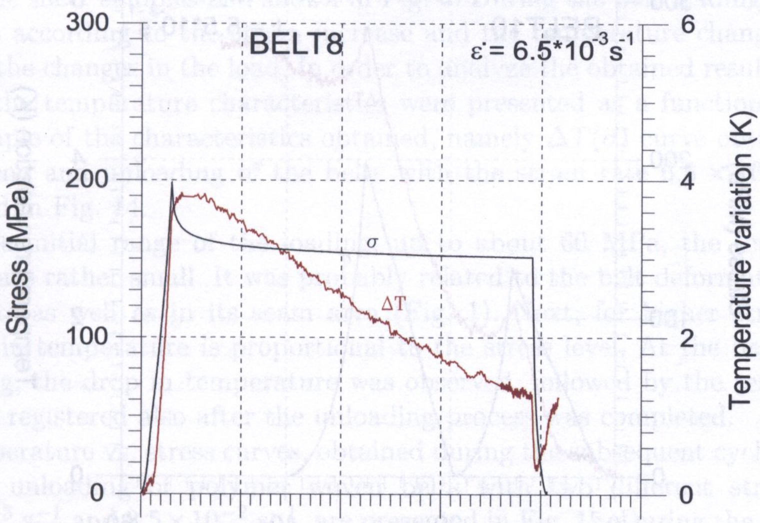

FIG. 11. Stress and temperature vs. time of woven polyamide belt subjected to tension and stress relaxation tests.

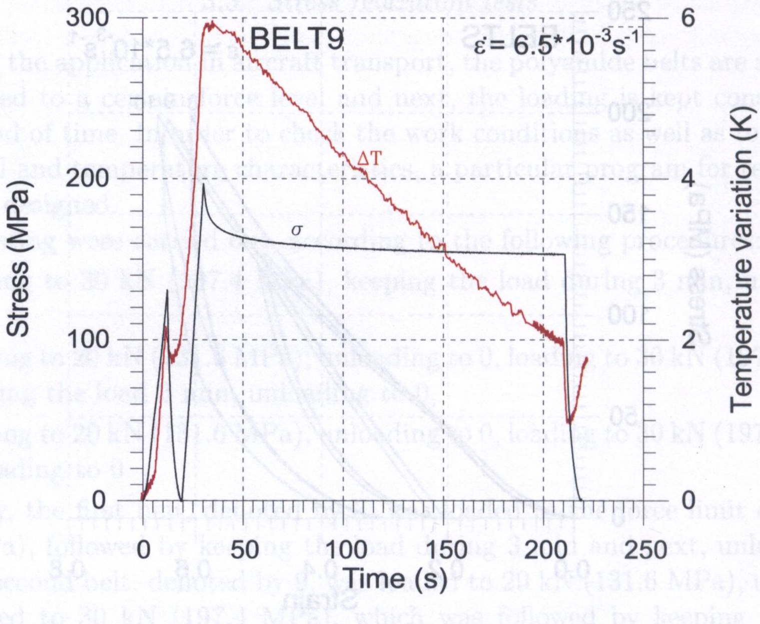

FIG. 12. Stress and temperature vs. time of woven polyamide belt subjected to loading, unloading and stress relaxation sequences in the second cycle of loading.

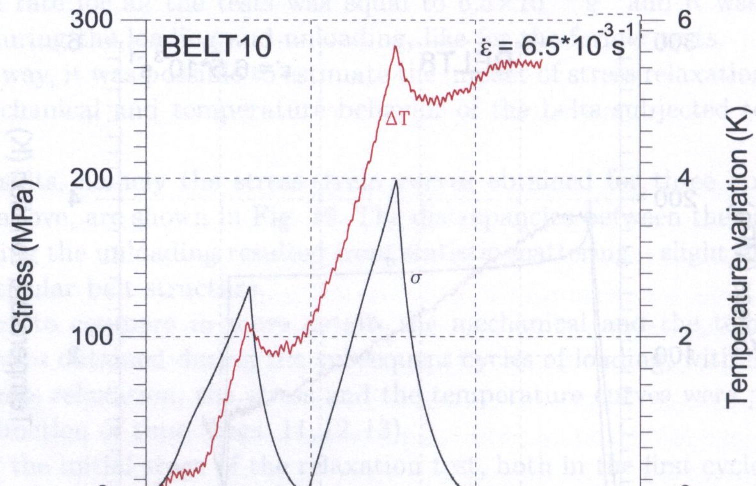

FIG. 13. Stress and temperature vs. time of woven polyamide belt subjected to two subsequent cycles of loading and unloading.

Such sudden temperature changes were not registered during the low cyclic loading-unloading test, without the relaxation stages (Fig. 13). Therefore, the temperature increments accompanying the relaxation process could be mainly caused by releasing the stresses of threads and fibers and following these, friction effects that occur in the complex belt structure (Fig. 2). Furthermore, the thermoelastic effect, positive in the case of negative stress change [4] can also influence the registered temperature increments.

Especially interesting effects were registered for the test with 2 cycles of loading and unloading, after the unloading was completed (Fig. 13). Namely, a contraction of the belt followed by the increase in stress up to 100 MPa and increase in temperature up to 1 K, were observed. This was probably caused by shrinking of the belt threads and fibers, subjected during the relaxation process to various local stresses.

From comparison of the results presented in Figs. 10–13 one can observe that the relaxation process influences the stress and the temperature variation during and after this process.

4. Thermomechanical couplings

The presented results pointed out that both the stress-strain characteristics as well as the temperature changes accompanying the process of loading of the belts, are quite different from those observed during deformation of the polyamide sheet samples and shown in Fig. 6. During the belt loading, the force increases according to the strain increase and the temperature changes are related to the changes in the load. In order to analyze the obtained results in more details, the temperature characteristics were presented as a function of stress. An example of the characteristics obtained, namely $\Delta T(\sigma)$ curve obtained during loading and unloading of the belts with the strain rate 6.5×10^{-3} s^{-1}, is presented in Fig. 14.

In the initial range of the loading, up to about 60 MPa, the temperature changes are rather small. It was probably related to the belt deformation in the grip parts as well as in its seam area (Fig. 1). Next, for higher stresses, the increase in temperature is proportional to the stress level. At the beginning of unloading, the drop in temperature was observed, followed by the temperature increase, registered also after the unloading process was completed.

Temperature vs. stress curves, obtained during the subsequent cycles of loading and unloading of polymer woven belts with two different strain rates: 6.5×10^{-3} s^{-1} and 3.5×10^{-2} s^{-1}, are presented in Fig. 15. During the initial two cycles of loading, similarly to the effect observed during former loading-unloading tests, the temperature changes registered for the stress level higher than 70 MPa were proportional to the stress value. In the subsequent cycles, the proportionality was observed just from the onset of the loading. Instead, the temperature decrements accompanying the subsequent cycles of unloading are rather small. It was caused by imposition of the positive effects of thermoelastic unloading and friction effects on the effects of heat exchange with the surroundings.

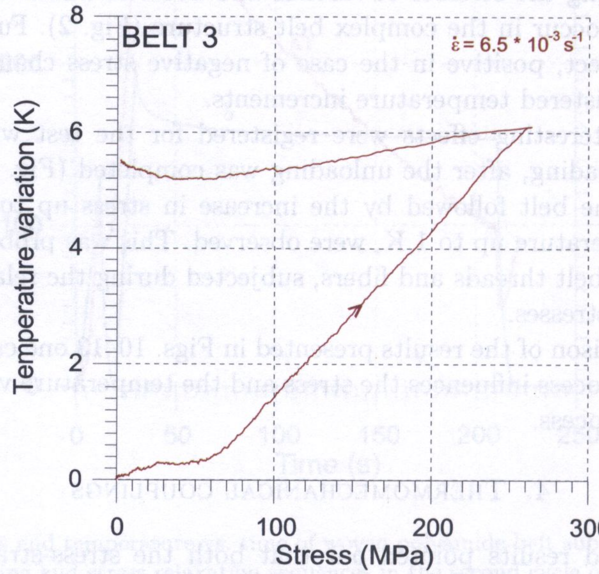

FIG. 14. Temperature changes vs. stress of woven polymer belt subjected to loading and unloading during tension test with the strain rate 6.5×10^{-3} s^{-1}.

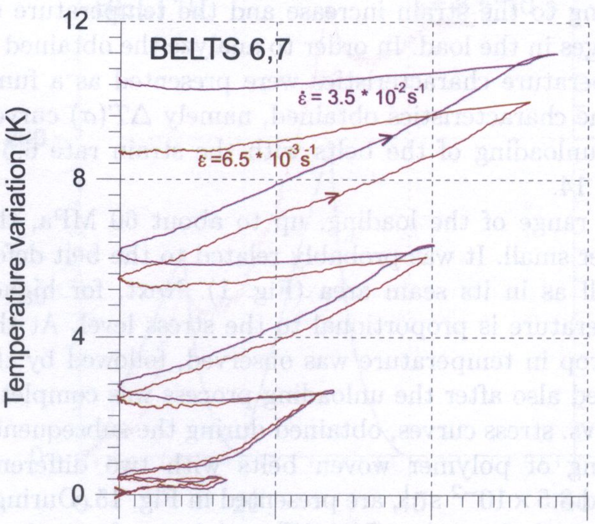

FIG. 15. Temperature changes vs. stress obtained for woven polymer belt during subsequent tension tests with strain rates 6.5×10^{-3} s^{-1} and 3.5×10^{-2} s^{-1}.

The temperature changes vs. the stress obtained during loading to 30 kN (stress about 200 MPa) and 3 min of relaxation followed by the complete unloading, are presented in Fig. 16. At the beginning of the stress relaxation process, an insignificant temperature increase of about 0.3 K was observed, probably caused by the urgent stress drop. It was followed by the temperature decrease of about 2.5 K, resulting from the heat exchange with the surroundings. During unloading, the temperature decreased at the beginning, which was followed by an increase in temperature, registered also after the unloading process was completed.

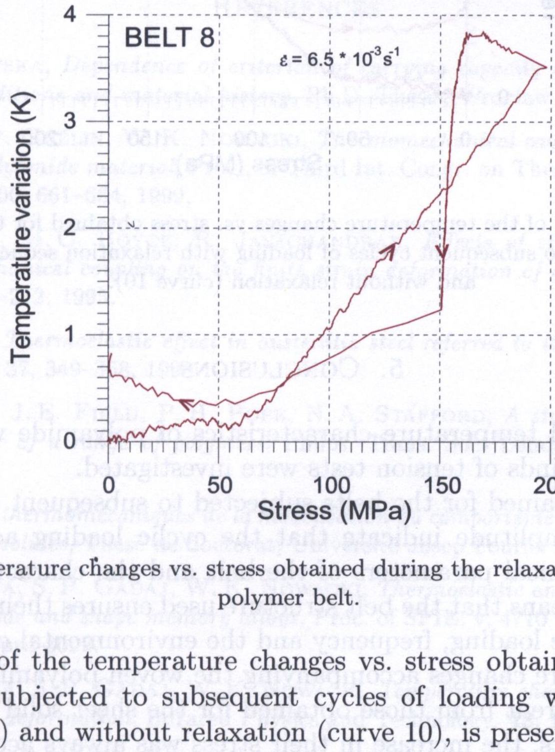

FIG. 16. Temperature changes vs. stress obtained during the relaxation test of woven polymer belt.

Comparison of the temperature changes vs. stress obtained for two woven polymer belts, subjected to subsequent cycles of loading with relaxation sequences (curve 9) and without relaxation (curve 10), is presented in Fig. 17.

One could observe that only during the initial stage of the stress relaxation process, the change in stress causes the change (increase) in the temperature. As it was mentioned before, such a temperature characteristics are probably caused by both the effects of the thermoelastic unloading as well as by the friction effects of the belt fibers. In other words, it may be a superposition of both the effects of the material as well as of the effects of the belt structure. During further stage of the belt relaxation, the temperature decreases as a result of the heat exchange with the surroundings. On the other hand, the character of temperature variation accompanying the unloading process does not change.

During the unloading, the temperature was reduced at the beginning, which was followed by the temperature increase, registered also after the unloading process was completed.

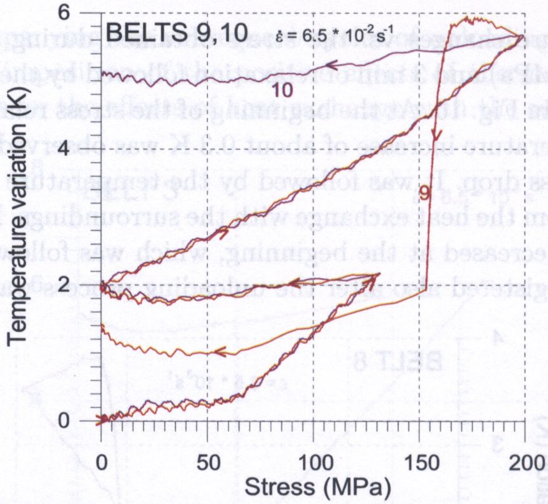

FIG. 17. Comparison of the temperature changes vs. stress obtained for two woven polymer belts subjected to subsequent cycles of loading with relaxation sequences (curve 9) and without relaxation (curve 10).

5. CONCLUSIONS

Mechanical and temperature characteristics of polyamide woven belts subjected to various kinds of tension tests were investigated.

The results obtained for the belts subjected to subsequent cycles of loading with increasing amplitude indicate that the cyclic loading actually does not change the mechanical parameters of the belt and the character of the stress-strain curves. It means that the belt structure used ensures their safe application in this range of the loading, frequency and the environmental conditions.

The temperature changes accompanying the woven polyamide belt deformation are quite different from those obtained for the sheet solid polyamide specimens. For the belts, the increase in their stress was always accompanied by an increase in their temperature. Such a character of the temperature changes indicated that in initial stage of loading, the friction effects of the fibers and threads, elements of the belt structure, mainly caused the heat production. For higher stresses, the temperature increased also due to plastic deformation of the fibers.

Temperature changes found for four subsequent cycles of loading and unloading reached 10 K. Under higher number of cycles, the increments in temperature may be much higher and they may significantly influence the extension of the belt and its strength. This may be strengthened in addition by low thermal conductivity of the polymers and weak heat exchange with surrounding.

The woven polymer belt exhibits during unloading certain properties of the shape memory due to their viscosity: even after complete unloading it shrinks, diminishing significantly its permanent deformation.

The relaxation process exerts an effect on the stress and the temperature run during and after the process of material testing.

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References

1. B. Gabryszewska, *Dependence of criterion of carrying capacity of plastic materials on the loading conditions and material history*, Ph.D. Thesis, Wrocław 1964.
2. S. P. Gadaj, P. Guélin, W. K. Nowacki, *Thermomechanical coupling during cyclic deformation of polyamide material*, Proc., of Third Int. Congr. on Thermal Stresses, Cracow, Poland, 13–17. 06. 661–664, 1999,
3. E. M. Arruda, M. C. Boyce, R. Jayachandran, *Effects of strain rate, temperature and thermomechanical coupling on the finite strain deformation of glassy polymers*, Mech. Mater., **19**, 193–212, 1995.
4. E. Pieczyska, *Thermoelastic effect in austenitic steel referred to its hardening*, J. Theor. Appl. Mech., **2**, 37, 349–368, 1998.
5. S. M. Walley, J. E. Field, P. H. Pope, N. A. Stafford, *A study of the rapid deformation behavior of a range of polymers*, Philos. Trans. Soc. London, **A, 328**, 783–811, 1989,
6. G. Bles, *Bases thermomécaniques de la modélisation du comportement des matériaux tissés et des polimers solides*, Thèse de doctorat, Université Josep Fourier Grenoble I, 2002.
7. E. A. Pieczyska, S. P. Gadaj, W. K. Nowacki, *Thermoelastic and thermoplastic effects in steel, polyamide and shape memory alloys,* Proc. of SPIE, v. 4710 – Thermosense XXIV, 1–4, 479–487, April 2002.
8. E. A. Pieczyska, S. P. Gadaj, W. K. Nowacki, *Temperature changes in polyamide subjected to tensile deformation*, Infrared Physics and Technology, **43**, 183–186, 2002.
9. E. A. Pieczyska S. P. Gadaj, W. K. Nowacki, T. Tobushi, *Thermomechanical investigation of martensite and reverse transformations in TiNi shape memory alloy*, Bull. Pol. Ac.: Tech. **52**, 3, 165–171, 2004.

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