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A Simulation of the Transient Self-heating Process in Dynamically Loaded Rubber-based Multilayers Reinforced Composites

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Abstract

The paper deals with an investigation of the transient process of heat generation and stabilization of temperature balance inside pneumatic tires during stationary rolling. The heat generation value have been obtained via integration of deformation over the cycles for each point of model. The function of heat generation rate have been created in each point based on previously defined cycles of deformation and experimentally obtained of loss modulus for materials. The temperature distribution of tire has been found within process of thermal stabilization.

Keywords

Heat generation, pneumatic tire, cycles of deformation, transient thermal analysis,

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Introduction

Elastomers are widely used in modern mechanical engineering, especially in transport. The most widespread are rubber elements and reinforced rubber composites. Analysis of characteristics of these elements is an important part in determination of operational characteristics of whole machine or mechanism. Typical operational conditions of the designs with elastomers and their composites are come with the dynamic load. It associates with two phenomena: fatigue damage accumulation and heat generation. The latter requires special on a attention as it can leads to self-heating of the design. Higher temperature in its turn can significantly change properties of material (elastic and strength characteristics). Moreover, it can increase the rate of ageing processes.

This research deals with investigation of heat generation in automobile pneumatic tire during its deformation at the stationary rolling. From practice it is known that the rolling process of pneumatic tires accompanied with the self-heating of its internal elements while at some points the temperature can rise to above 80°C and over. In addition to previously outlined the changing of thermal conditions in the tire leads to a changing of internal pressure and creates an additional thermal stress state.

Heating process of automobile tire is the result of several processes. The first one is the conversion of the mechanical energy of cyclic deformation of rubber-like materials into heat. The second is due to internal friction between the different components of complicated composite structures and last is external friction of tire with a road surface.

It should be noted that due to the presence of complicated strain state, curvilinear geometry and multilayer structure the temperature field is considerably non-uniform, that leads to changing in the stress-strain state of tire and can leads to formation and grow of internal defects. Thus, an actual task is to study the processes of formation of temperature distribution in the tire during its operation.

1. The problem statement

This paper deals with theoretical modelling of the transient thermal analysis of the tire up to a temperature balance during it stationary rolling. The problem was solved in three stages (Fig. 1).

The first stage is solving of static problem of tire interaction with the road surface. Besides the tire was loaded by internal pressure of 0.25 MPa and a vertical load of the weight of the vehicle. The analysis of results obtained in this stage allows to find the strain cycles of one revolution in each of the layers.

The second phase deals with determination of the heat generation rate in each point. To achieve this goal the amount of energy released per cycle of deformation was determined. In addition, loss modules were determined previously by experiment for all materials of tire.

The third stage consists of solving of transient convective heat transfer problem. The function of heat generation rate was applied as the load during the calculations. This function was determined at the step 2.

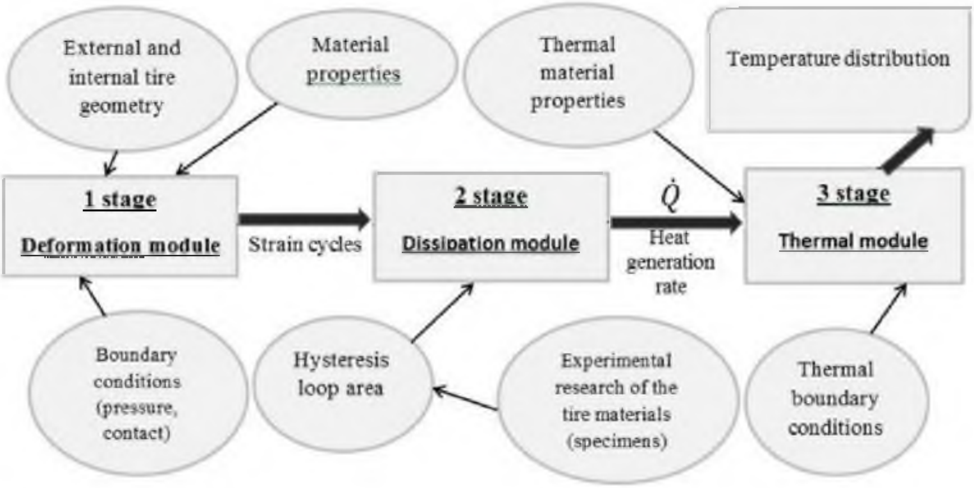


Figure 1. The mechanism of solving the problem of convective heat transfer

2. Finite-element modelling

In this paper the pneumatic tire 205/55R16 model is considered. During the simulations the main design features (Fig. 2) and material properties were taken into account (see. Table. 1).

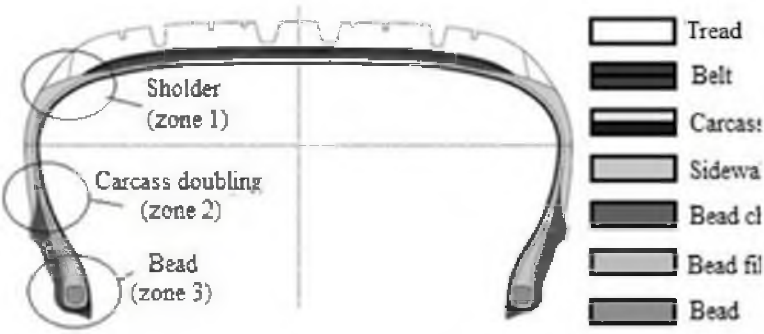


Figure 2. Structure of pneumatic tire

The main calculations have been carried out on the base of FE-modeling.

The problem is solved in three stages, the first and last of which require specific models. The first FE model was designed to solve the problem for determination cycles of deformation. The 8-nodal finite element with 3 degrees of freedom in the node was used. The second FE model is needed to solve the problem of convective heat transfer. The 20-nodes finite element with 1 degree of freedom in the node was used to create this model.

Table 1. Materials properties

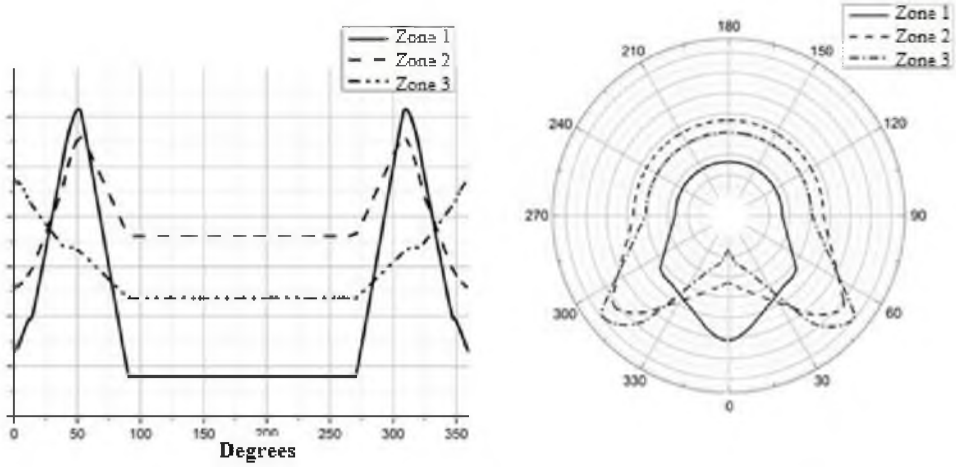
	Elasticity modulus	Poisson ratio	Density	Heat capacity	Thermal conductivity
	E, MPa	υ	ρ, kg/m^3	c, J/kg·C^0	k, W/m·C^0
Tread	3.00	0.49	1200	1020	0.273
Sidewall	3.74	0.49	1200	1020	0.273
Bead chafer	7.00	0.49	1200	1020	0.273
Filler	16.00	0.49	1200	1020	0.273
Rubber matrix	6	0,49	1200	1020	0.273
Carcass (cord)	77120	0,3		1020	0.273
Belt (cord)	74730	0,3		1020	0.273

FE meshes of both models had the same position in the space.

Figure 3. FE- model, a – full FE-model of tire, b – segment of tire

In the first stage of the analysis were carried out in the framework of multiscale approach of FE modeling. Its technology is described in [1]. Physical nonlinearity, which occurs due to the presence of large deflections and strains is accounted by using the model of Neo-Hooke [2] (which accurately approximates the behavior of rubber materials with about 20% strains deformation). Rubber-cord plies of carcass and belt have been modeled as orthotropic with averaged characteristics for each direction according to the generalized Hooke's law [2]. The curvilinear orthotropy of mechanical properties of a rubber-cord layers was realized by introduction finite-toroidal local coordinate systems in which axes directions repeat geometry of corresponding layer [2]

The strain cycles per revolution were defined in all layers of the tire. These calculations showed that the largest stresses were observed along the lines with the circumferential coordinate 50 and 307 degrees. The zones correspond to the change from the contact region to the contactless zone. The largest stresses were observed in the of belt layer. Cycles of stress state (the ratio of current stress to ultimate tensile strength) is shown on the Fig. 4 in polar coordinates (0 ° corresponds to the tire contact area with the road surface).



a *b*

Figure 4. Strain cycles of specific zones
a - in the Cartesian coordinate system, b – in polar coordinates
zone 1 – tire shoulder, zone 2 –zone of carcass semi-coupling, zone 3 – bead

As result of first stage, the strain cycles in each layer were obtained. Also they were divided into 4 categories by strain value and saved for using this data in the second phase of overall process.

The second stage is the determination of heat generation rate per unit volume. According to [3] it can be calculated as follows:

$$Q = \frac{\Delta W}{T_c} = \frac{1}{T} \cdot \int_0^{T_c} \sigma_{ij}(\tau) \cdot \frac{d\varepsilon_{ij}(\tau)}{dt}, \tag{1}$$

where ΔW – Hysteresis loss, T_c – period (during one rotation), σ_{ij}, ε_{ij} – stress and strain tensors respectively.

In the literature [3] definition of Q is often simplified through schematization of strain cycles. It is considered that stress and strains are harmonic process with the equal frequency, but with phase shift. Then expression of ΔW simplifies to

$$\Delta W = \pi \ddot{E} \varepsilon_1^2, \tag{2}$$

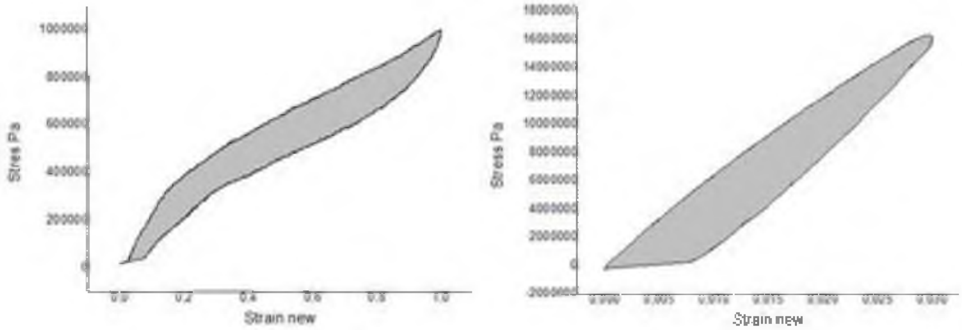
where $\ddot{E}$ – loss modulus, which for the corresponding materials is determined experimentally, by tests with cyclic loading; ε_1 – the maximum principal strain, which have been identified and saved for each FE previously.

The loss modulus for each material is found experimentally on the base of cyclic tension tests. Experiments were carried out with displacement control conditions. The plain specimen of geometry corresponds to standards for mechanical tests of rubber-like materials and rubber-cord composites ISO 527-2 1A. A displacement control load were posed i.e. fixed values of strains were set for specimen. The results are automatically recorded, for each test in real time and have been recorded each 0.1 seconds.

Hysteresis loop areas were determined by experiments (Figure 5) and loss modulus were found for all materials (Table 2), according to following formula

$$\ddot{E} = \frac{\Delta W^*}{\pi (\varepsilon_1^*)^2}, \tag{3}$$

where ΔW^* – hysteresis loop area which was defined in the experiment (Figure 5); ε_1^* - strain amplitude, that was applied to the specimen.



a b

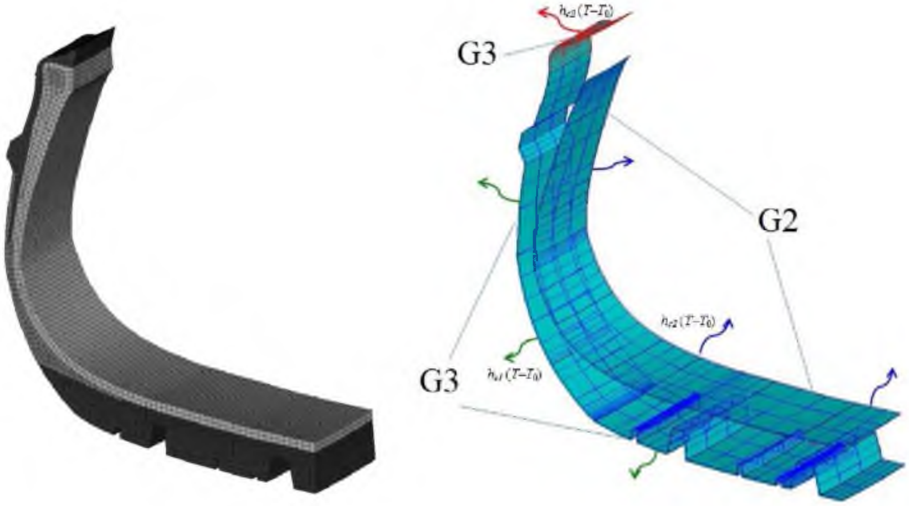
Figure 5. Hysteresis loops for different materials of tire layers: a – sidewall, b – belt

Table 2 Loss modulus of tire materials

	Carcass	**Belt**	**Filler**	**Sidewall**	**Tread**
E'', MPa	1.830	9.490	0.136	0.012	0.081

The last stage is presents the solution of the convective heat transfer problem.

FE model was built to solve this problem. Fig. 6, *b* illustrates the surfaces with different boundary conditions.



a *b*

Figure 6. FE – model (*a*) and boundary conditions (3rd stage) (*b*)

The temperature (T_0,C°) and convective heat transfer coefficient h_c, W/m^2C° were applied as the boundary condition on the external (G2), internal (G3) surface of tire and on the place of interaction with the disk (G3).

So on the surface G1: $T_o = 25$ C°, $h_{c1} = 16{,}18$ W/m^2C° ;

on the surface G2: $T_o = 25$ C°, $h_{c2} = 5{,}9$ W/m^2C°;

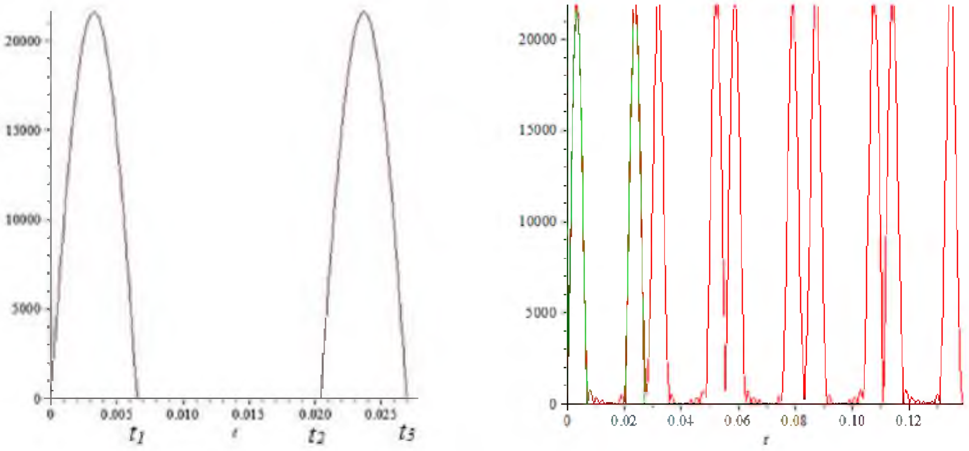
on the surface G3: $T_o = 25$ C°, $h_{c3} = 88000$ W/m^2C°;

Heat generation rate $\dot{Q}$ was applied in each FE as a load that previously was expanded in Fourier series.

Schematic cycle of heat generation pulse according to corresponding characteristics of strain cycles (Fig. 7) has a form:

$$\dot{Q} = \begin{cases} \dfrac{\Delta W \cdot \pi}{2 \cdot t_1} \sin \dfrac{\pi t}{t_1} & t \in (0, t_1) \\ 0 & t \in (t_1, t_2), \\ \dfrac{\Delta W \cdot \pi}{2 \cdot (t_3 - t_2)} \sin \dfrac{\pi (t - t_2)}{(t_3 - t_2)} & t \in (t_2, t_3) \end{cases} \qquad (4)$$

where – ΔW is determined by the formula (2).

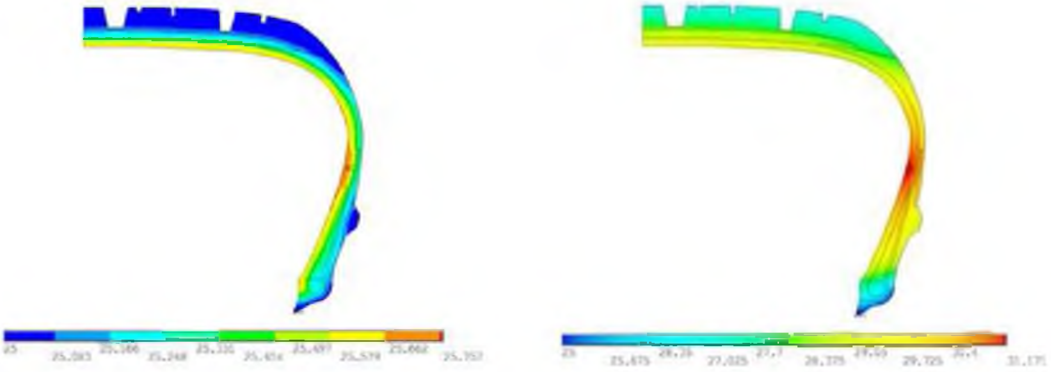


a b

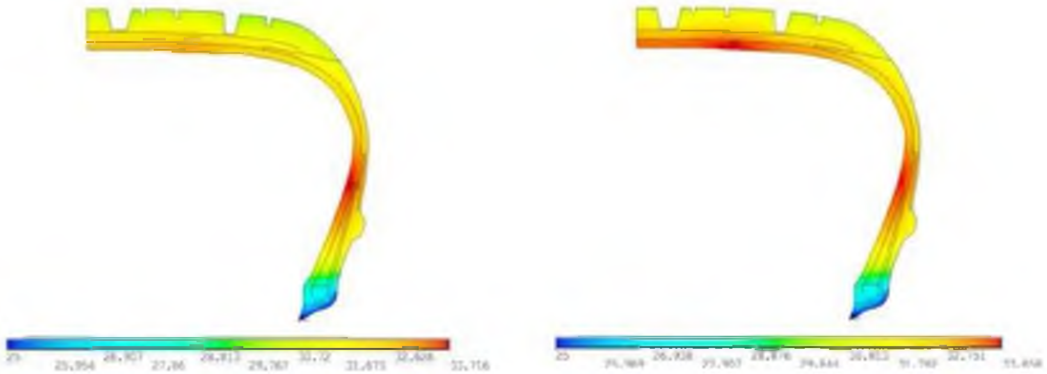
Figure 7. Heat generation cycle: a – pulse of one revolution,
b – Fourier decomposition (5 wheel revolutions)

As a result, we obtain the temperature distribution in the tire for different periods of time. According to Fig. 8 carcass zone is the most heated due to presence in it larger strains in comparison with other layers.

Fig. 9 shows the character of heating of different parts of the carcass (with the highest temperature). According to Fig. 9 the active heating of tire takes place at first 15 minutes and after 30 minutes the temperature distribution is stabilized.

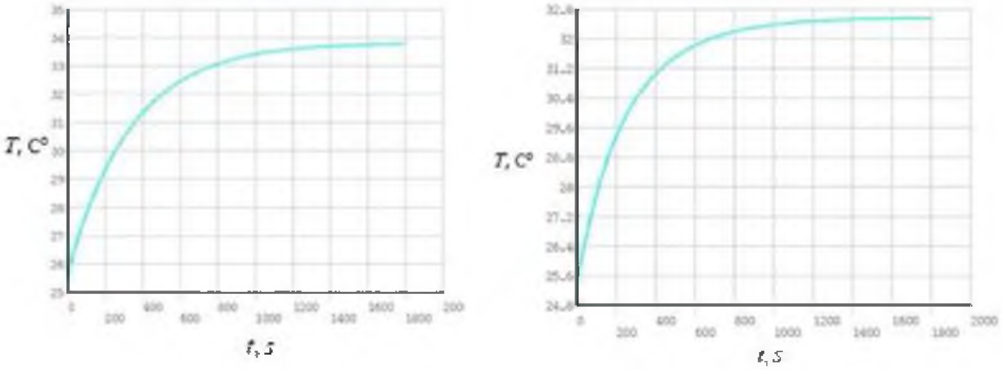


a B



c D

Figure 8. Temperature distribution in the tire:
a – 0.15 min., b – 0.6 min., c – 12.75 min., d – 30 min.



a B

Figure 9. Graphic of heating of tire layers: a – carcass (contact zone), b – carcass (bead)

Conclusions

Two FE-models of sector of pneumatic tire were created. The first one for solving of the structural problem (determining strain cycles) and the second for convective heat transfer problem. Based on the strain cycles that were previously schematized the heat generation model of the tire during its rolling was created. The necessary data for implementation of this model (loss modulus of materials) were obtained by experiments. As a result of solving this problem we have received the temperature distribution in the tire until the moment of stabilization of the thermal state.

References

[1] Larin O.O., Petrova Ju.A., Mateichyk V. Two-scale approach to modelling of pneumatic tyres *Systems and means of motor transport. Selected Problems. – Monographia N 4. Seria: Transport.* Rzeszow: Politechnika Pzeszowska Im. Ignacego Lukasiewicza, 2013, pp. 123-128

[2] Larin O.O., Petrova Ju.A. A sub-modeling procedure on stress cycles determination of pneumatic tire structural elements. *NTU «KhPI» Bulletin: Series «Dynamics and Strength of Machines»*, 2014, No. 57, p. 37-49. [in Ukrainian]

[3] Cho J.R., Lee H.W., Jenog W.B. Jeong, K.M., Kim K.W. Numerical estimation of rolling resistance and temperature distribution of 3-D periodic patterned *Int. J. of solids and structures*, 2013, № 50, p. 86-96.