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Temperature and wear characteristics of TBR tread rubber and its constitutive characterization

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An auxiliary heating device for rubber wheels is developed based on the Akron wear testing machine. The temperature dependence of the rubber wear is analyzed. The results demonstrate that the relationship between the wear and temperature can be described by a quadratic polynomial function. The wear resistance at high temperature is related to the glass transition temperature of the rubber. At high temperature, butadiene rubber (BR) exhibits higher wear resistance than natural rubber (NR) and styrene butadiene rubber (SBR), due to its higher glass transition temperature. In addition, the friction energy of the LAT100 wear is calculated by the finite element method. A power function relationship between the wear and the friction energy is obtained by fitting the test data. Finally, a comprehensive expression of the rubber wear as a function of temperature is set up based on the relationship between temperature, wear volume, and frictional energy. This work improves the thermo-mechanical coupling model of rubber wear, and provides a new theoretical basis for more accurate analysis of rubber wear.

Keywords: Wear, Rubber, Temperature, Thermo-mechanical coupling model

OBJECTIVES AND BACKGROUND

Rubber products such as tires take advantage of their viscoelasticity and large nonlinear deformation capability. The investigation of tire wear was originally initiated by studying the mechanism of rubber wear. Grosch and Schallamach [1], Savkoor [2], Schallamach [3, 4] and a few other scholars first conducted a systematic research on rubber wear. Grosch and Schallamach studied the relationship between the temperature and velocity of rubber friction, and analyzed the surface pattern of sliding rubber wear (Schallamach wear pattern). Savkoor and later Persson *et al.* [5, 6] performed comprehensive research on the bond friction theory of rubber. In recent years, scholars worldwide focus on the aspects of material improvement and material aging properties [7-13]. These studies provide guidelines and detailed understanding of rubber wear mechanisms. Nevertheless, due to the complexity of the rubber wear process, it is necessary to study the thermodynamic behavior of rubber wear. Scholars all over the world have done a lot of research on this topic. The tire is usually working at much higher temperature than the ambient temperature, and the wear performance is lowered at high temperature. Thus, it is very important to study the effect of temperature on the wear properties. This paper chose truck bus radial (TBR) tire tread rubber as the test subject, and used a newly-developed temperature abrasion test device to test the temperature of rubber abrasion wear. The wear model of rubber can be characterized as a function of friction energy and temperature.

MODELING OF THE RELATIONSHIP BETWEEN RUBBER ABRASION AND TEMPERATURE

Data regression analysis was conducted based on a variable temperature wear experiment of the rubber. A quadratic polynomial mathematical model describing the relationship between rubber wear and temperature was established.

Experiment

Testing equipment

Based on the Akron wear testing machine, an auxiliary equipment and experimental method of variable temperature wear were developed (shown in Figure 1). The experimental method was different from the traditional rubber wear testing method which performs the experiment at high temperature through changing the ambient temperature. In this test, the way of heating the rubber wheel was closer to the actual working conditions of the tires. In addition to the functions of the traditional Akron wear machine, the main new features are as below:

(i) A heating wire was used to heat the rubber wheel. A thermocouple was used to measure the temperature of the rubber wheel. The temperature was controlled by the temperature control instrument. The temperature of the rubber wheels ranges from room temperature to 100ºC. The ambient temperature for the experiment was 25ºC.

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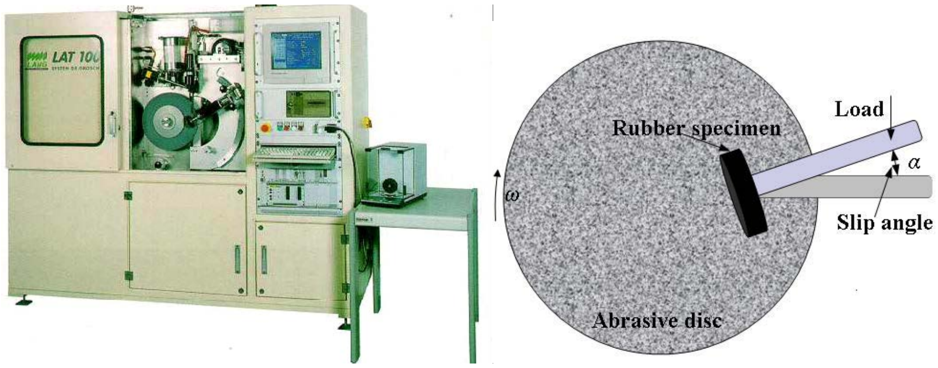


A) Testing machine B) Wear mechanism

Fig. 1. LAT100 wear test machine and schematic

(ii) A sand dispersing device was added, and the type of sand was properly chosen to solve the problem of surface adhesion of rubber wheel crumbles which may affect the precision of the test.

(iii) The wear rubber sample and the rubber wheel were pasted together by low temperature sulfide curing to prevent slippage of the rubber sample from the rubber wheel at high temperature.

Experimental material

Four TBR tread rubbers were tested: A011 (NR+N234+SiO_2), A019 (NR+N234), A015 (NR+N134), A017(NR+BR+N234).

RESULTS AND DISCUSSION

The variable temperature wear testing device was used for the rubber wear test under different temperatures. The test results are analyzed and discussed below.

The Akron standard rotation distance was 1.61 km. We took half the distance for the grinding test, which is 1709 rotations. Each test was performed two times to get an average of the wear data. The experimental data are shown in Table 1.

Because the Akron wear takes place at low speed and moderate temperature, the surface temperature cannot reach above 40ºC. In order to eliminate the effect of friction heat between the rubber wheel and grinding wheel in the experiments, the experimental temperature was set above 40ºC when the relationship between the temperature and wear was analyzed. Figure 2 shows the relationship between the wear and temperature. The dependence of the wear on temperature can be described by a quadratic polynomial function which has a decent fitting accuracy. The four types of TBR tread rubber have different using purposes. A011, A015, A019, A017 are intended for low rolling resistance, integrated pavement, high-speed road, and rough road, respectively. Through the analysis of the data (Table 1 and Figure 2), we concluded that at low heat tread temperature, A011 was the most sensitive while A017 used for the rough road was the least sensitive to the temperature.

Due to the use of NR and BR in the A017 tread rubber and the higher glass transition temperature of BR, its high temperature wear resistance is reasonable. It can be predicted that the high

Table1. The wear performance of different TBR tread rubbers at different temperatures (load of 26.7N, angle of 15°)

Distance, m	Temperature, ºC	A011, g	A015, g	A017, g	A019, g	A015-1, g	A017-1, g	A019-1, g
1000	40	0.12854	0.11464	0.09779	0.11046	0.07737	0.06225	0.07118
1000	60	0.15220	0.13597	0.15559	0.13454	0.10019	0.08323	0.08738
1000	70	0.19589	0.17366	0.16259	0.16510	0.13096	0.10803	0.13263
1000	80	0.23709	0.21136	0.17829	0.19319	0.15428	0.12911	0.17415

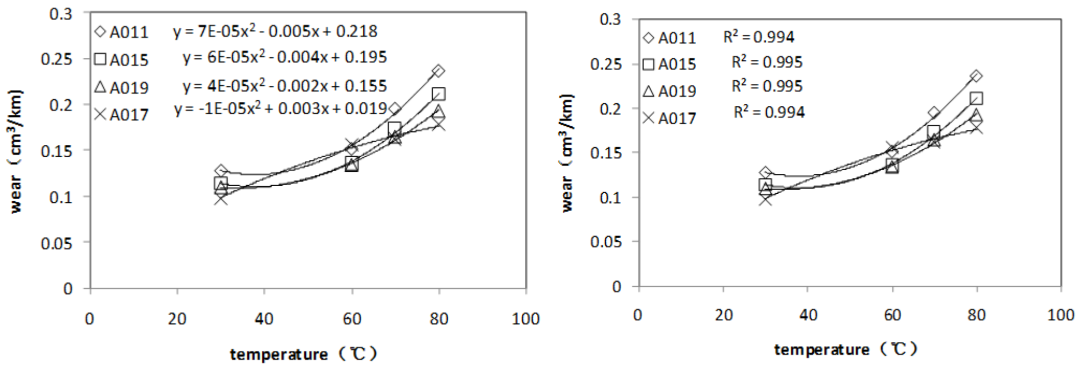


Fig. 2. Four types of tread rubber wear as a function of temperature under 26.7N, 15°, 76 r/min

temperature wear resistance of SBR will be poor, because its glass transition temperature is lower than that of NR. Nevertheless, things can be different in the actual use of the tires. By comparing the wear resistances at the same temperature, BR will cause the tire to roll at a higher temperature in the actual use due to the higher heat generation. The wear resistance also needs to be reevaluated.

Meanwhile, the wear resistance is only one of the important parameters of the tire performance. High temperature will lead to more quality-related problems of the tire, which is perhaps the reason that very few BR are applied to high-speed and long-distance tires for truck and passenger cars.

The experimental results show that there is a quadratic polynomial relationship between the rubber wear and the temperature:

$$A_T = a \bullet T^2 + b \bullet T + c \quad (1)$$

where AT is wear quality (g), T is rubber wheel temperature (ºC), *a*, *b* are care fitting coefficients. The sensitivity analysis of the temperature can be performed by a simple first-order and second-order derivative. Smaller *a* and *b* correspond to better wear resistance at high temperature.

LAT100 WEAR TEST OF RUBBER MATERIAL AND CALCULATION OF FRICTION ENERGY

LAT100 wear test

(1) Test device: we used a LAT100 abrasion rubber wear testing machine made by VMI company, Holland, which is widely used in rubber industry (Figure 3).

(2) Test principle: the contact surface of the LAT100 abrasion machine is a rotary disc. A certain angle and load is set for the rubber wheel, the rotary disc drives the rubber wheel to rotate at the set speed. Infrared scanning and force sensor are used to measure the longitudinal force, lateral force, and the surface temperature. The amount of the rubber wear is determined by weighing the debris that the rubber wheel was ground out during the test (Figure 3).

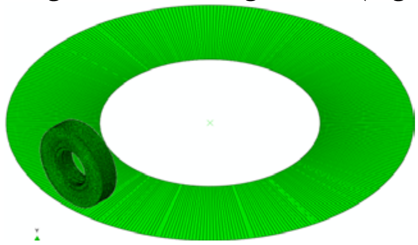


Fig. 3. Finite element modeling of the test

(3) Test conditions: load (N): 30. speed (km/h): 5, 10, 15, 20. deflection (°): 0°, 15, 30°, 40°. Rubber wheel: Φ 80 mm×δ 17 mm. Three types of samples were prepared for each experimental condition. The total data points were 48. Ambient temperature: 25ºC.

EXPERIMENTAL RESULTS

The experimental results are shown in Table 2.

Finite element analysis of the mechanical properties of rubber LAT100

Finite element modeling

The finite element model of tire wear was established based on ABAQUS and is shown in Figure 4. The linear elastic model was adopted to describe the constitutive relation of the rubber. Element type of CAX4R was adopted to describe the rubber property. The number of elements per section was 829. The number of sections was 74 and the total number of elements was 61346. The contact surface of the grinding wheel was set as rigid body. The friction coefficient was 0.40. Wear disc rotated with the angular velocity ω. The load was exerted on the center of the rubber wheel.

Table 2 Wear results of LAT100 and friction energy simulation data

Slip angle, °	Velocity, km/h	Distance, m	Weight loss, g	Surface temperature, ºC	Frictional energy density, J/m^2
0	5	1000	0.0006	22.6	1076.9
0	10	1000	0.0007	24.6	1915.9
0	15	1000	0.0020	25.1	3314.9
0	20	1000	0.0028	25.4	4421.5
15	5	1000	0.0444	32.3	284268.9
15	10	1000	0.0746	37.4	568557.3
15	15	1000	0.0679	43.9	852838.4
15	20	1000	0.0817	48.3	926282
30	5	1000	0.1634	41.0	623953.3
30	10	1000	0.1731	41.7	1017191
30	15	1000	0.2778	51.0	1525796
30	20	1000	0.4078	44.4	2034337
40	5	1000	0.1448	27.7	898665.4
40	10	1000	0.2096	30.3	1822607
40	15	1000	0.4108	32.4	2228761
40	20	1000	0.7877	32.5	2971692

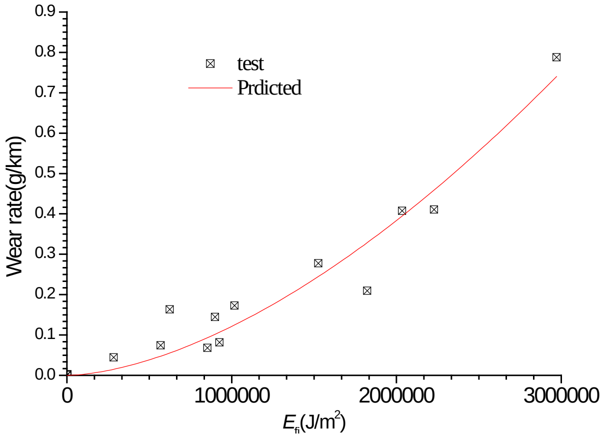
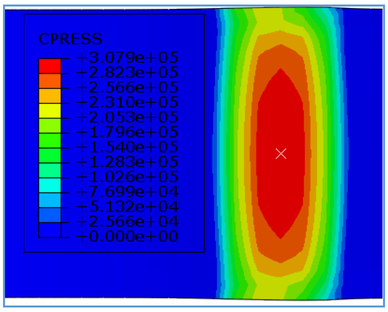


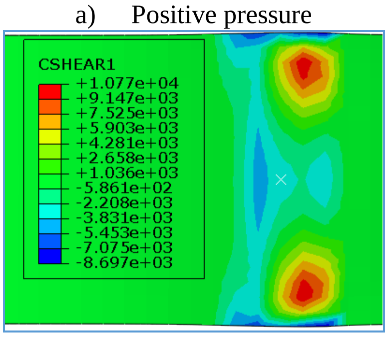
Fig. 4. Relationship between measured wear rate and friction energy

RESULTS AND DISCUSSION

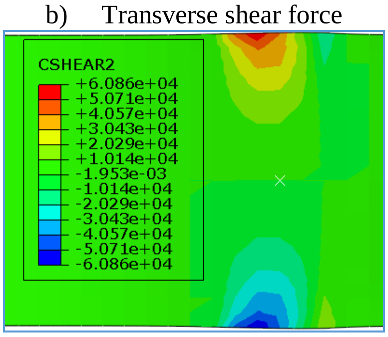
The simulation conditions were the same as the LAT 100 experimental conditions: load (N): 30; speed (km/h): 5, 10, 15, 20; deflection (°): 0, 15, 30, 40. Figures 5 to 7 show the results of the contact pressure, transverse and longitudinal shear stress, and slip under the condition of load 30 N, speed 20 km/h, degrees 0° and 30°.



a) Positive pressure

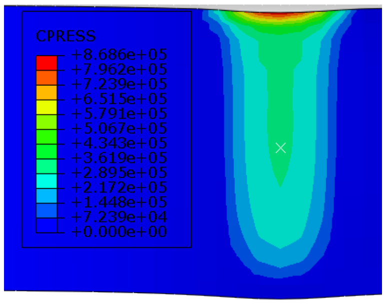


b) Transverse shear force

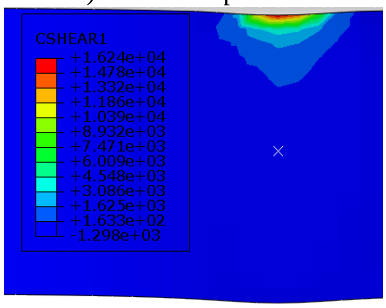


c) Longitudinal shear force

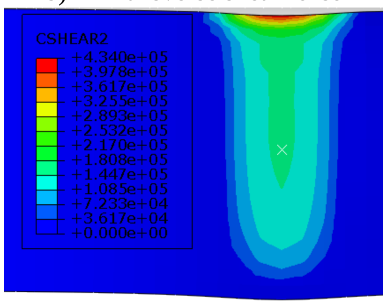
Fig. 5. Positive pressure, transverse and longitudinal shear stress distribution under 0° (unit: N/m^2)



a) Positive pressure

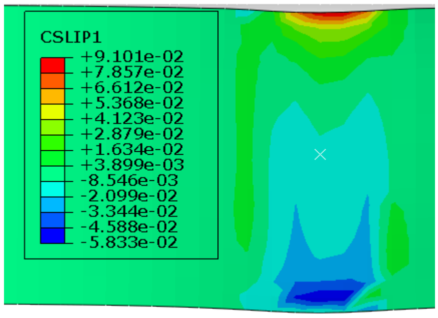


b) Transverse shear force

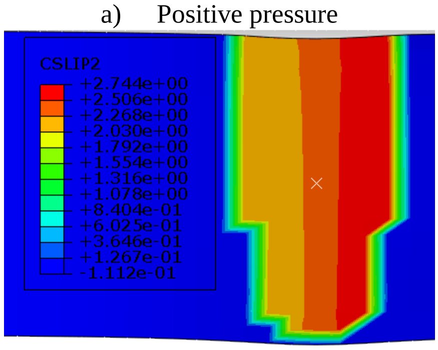


(c) Longitudinal shear force

Fig. 6. Positive pressure, transverse, and longitudinal shear stress distribution under 30° (unit: N/m^2)



a) Positive pressure



b) Transverse shear force

Fig. 7. Vertical and horizontal sliding distance under 30 °(unit: mm)

Friction energy calculation and experimental fitting

Here we calculate the longitudinal and transverse shear forces of each contact element in the contact surface between the rubber wheel and the wear disc. The two shear forces are expressed as: $\tau_i = \tau_{eq} \frac{\dot{\gamma}_i}{\dot{r}_{eq}}$ (i=1,2) (2)

where $\tau_{eq} = \mu p$, τ_{eq} is the frictional stress. μ is the friction coefficient. P is the normal contact force. $\dot{r}_{eq} = \sqrt{(\dot{r}_1)^2 + (\dot{r}_2)^2}$. $\dot{\gamma}_i$ is the tangential slip velocity. The subscript 1 represents longitudinal, 2 represents horizontal.

The formula for calculating the frictional energy of each element is:

$$W_{elem} = \tau_{eq}\dot{r}_{eq} \quad (3)$$

The formula for calculating the total friction energy density per round of rubber wheel is

$$E = \left(\int_0^L \sum_{i=1}^n w_i \right) \Big/ S \quad (4)$$

where w_i is the frictional energy of each element in the ground. L is rubber perimeter, *n* is the total number of elements that rubber wheel is in contact with the ground at a given time. $S = 0.5\pi\phi^2\delta$. Φ, δ and S are the diameter, thickness and grounding area of the rubber wheel, respectively.

Table 2 shows the experimental results of the LAT100 wear test. The friction energy density was obtained from the simulation result. The wear and surface temperature of the rubber wheel rise with the increase of the speed and angle.

The wear prediction model can be obtained from the above results:

$$A_E = C_E E^m \quad (5)$$

In the formula, CE= 1.3129E-11, which is the material constant. m=1.66, which is the relational index.

Figure 7 shows that there is a power function relationship between the measured wear rate and the simulated friction energy. The measured results are in good agreement with the simulation results.

WEAR ENERGY MODEL CONSIDERING TEMPERATURE EFFECT

The relationship between temperature, friction energy, and wear can be summed up as follows:

(1) Rubber heat originates from the rubber friction energy dissipation and the hysteresis heat due to viscoelastic deformation. The effect of speed and temperature on wear can be characterized by a single temperature variable according to the Williams-Landel-Ferry equation. So it is more reasonable to focus on the influence of temperature, because the effect of speed on wear is mainly from the rise of temperature. There is a quadratic polynomial relation between the wear and the temperature.

(2) The effect of load and slip on wear can be expressed by the friction energy. There is a power function relationship between the rubber wear and friction energy. Finite element analysis was used to fit the power function relationship between the rubber wear and friction energy to obtain the power exponent and relation constant.

Assuming that under normal temperature T0 and constant speed V0, wear capacity is A0. E0 is its corresponding friction energy. The relative expression of the relationship between wear and friction is:

$$A_{rel} = C_E \bullet \left(\frac{E}{E_0} \right)^m \quad (6)$$

Similarly, the relative expression of the relationship between wear volume and temperature is:

$$K_{rel} = \frac{A_T}{A_{T0}} = (aT^2 + bT + c) \big/ A_0 \quad (7)$$

The expression of rubber wear model considering temperature influence is:

$$A = A_{rel} \bullet K_{rel} = C_m E^m \bullet (a_1 T^2 + a_2 T + a_3) \quad (8)$$

The wear thermal coupling model for tire finite element analysis can be expressed as:

$$A_{ij} == C_m E_{ij}{}^m \bullet (a_1 T_{ij}{}^2 + a_2 T_{ij} + a_3) \quad (9)$$

where $\boldsymbol{A}_{ij}$, $\boldsymbol{E}_{ij}$, $\boldsymbol{T}_{ij}$ are for each unit node wear, friction energy and temperature, respectively. The i, j for the node number: i, j=1,2,3..., M is the power exponent, C_m, a_1, a_2, a_3 are constants, and their values are related to the formulation and working conditions of the rubber.

CONCLUSIONS

In this paper, the relationship between temperature, friction energy, and rubber wear was studied. In particular, the influence of temperature on wear was investigated, which further improved the thermal-mechanical coupling model.

(1) There is a quadratic polynomial relation between the wear and temperature. The wear of rubber has a significant temperature dependence. The relationship between rubber wear and temperature can be described by quadratic polynomials. The wear resistance at high temperature is related to the glass transition temperature of the material itself. The glass transition temperature of BR is higher than that of NR and SBR, which shows better characteristics of wear resistance at high temperature.

(2) There is a power function relation between the wear and friction energy. Based on the LAT100 wear test machine, wear experiments were carried out under various conditions, which can be calculated using finite element simulation, fitting wear on friction power function relation expression, and power index and relation constants.

(3) Temperature model of tire wear. The comprehensive wear model of rubber can be represented by two variables: friction energy and temperature. The thermal coupling model of tire wear for finite element analysis can be expressed as:

$$A_{ij} == C_m E_{ij}{}^m \bullet (a_1 T_{ij}{}^2 + a_2 T_{ij} + a_3)$$

The friction heat generation and accumulation of the tire due to extreme working conditions need further research because it is difficult to be measured and moreover, it is accompanied by the complex process of thermal degradation and chemical changes.

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