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Friction and wear

WEAR UNDER VIBRATION CONDITIONS OF SPHEROIDAL GRAPHITE CAST IRON MICROALLOYED BY Sn

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ABSTRACT

The testing rig and appropriate testing procedure have been developed for the study of abrasive wear under normal vibration load of selected specimens. Specimens were made of spheroidal graphite cast iron microalloyed by various percent content of tin (Sn). Experimental results on the influence of the vibration velocity and Sn content upon wear have been obtained.

Keywords: wear, vibrations, spheroidal graphite cast iron.

AIMS AND BACKGROUND

The kinematic pairs in machines and mechanisms always operate under lower of higher amount of vibration load caused by various reasons. The parameters of these vibrations undergo a wide range of changes, especially in transitional non-stationary operation regimes.

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Vibrations have an ambiguous effect on the tribological parameters of some tribosystems: static and kinetic coefficient of friction, wear, contact conductance, contact strength, noise, temperature rise, lubricant layer thickness, etc. Tribological parameters depend on the complex influence of a number of 'input' parameters: vibrations, loading, sliding/rolling speed, working temperature, type of friction, shape and size of contact, working medium (lubricant, vacuum, air, abrasive particles, acid medium), chemical composition of the elements, surface physical-mechanical properties and microstructure, roughness, etc.[1]

Vibrations in most cases intensify the wear processes, which affects in turn the vibration parameters[2–5]. The basic ways to diminish the vibration effect on wear are:

- Wear resistance improvement through the control of bulk material properties;
- Contact surfaces wear resistance improvement through the surface modifications and coatings;
- Development and application of the appropriate lubricant and lubrications;
- Optimal design of contact (kinematic) pairs.

The spheroidal graphite cast irons are a high strength construction material with a complex of properties which make them different from the conventional Fe-C alloys. They show high tensile strength, high plasticity, low susceptibility to stress raise, good wear resistance and good damping ability[6–8]. The spheroidal graphite cast irons meet a wide scope of tribological application in machinery construction, engineering and transport. They are used in the production of reduction gears, plain bearings, guide bars, gear wheels, etc. They are also utilized for the production of building equipment elements, agricultural and mining machines, milling systems, pumps, flotation equipment, etc. which work in normal and aggressive environments under conditions of dominant abrasive and erosive wear[9–15].

The aim of the paper was to apply the developed test rig and test procedure, for the experimental study of abrasive wear under vibration conditions, on the investigated specimens. Specimens were made of spheroidal graphite cast iron with improved mechanical and tribological properties through the microalloying with various tin (Sn) percentages. In addition, the influences of vibration speed and Sn percentage on tested specimens wear characteristics were analysed. The investigations were carried out at the Tribology Centre of the Faculty of Industrial Technologies at the Technical University of Sofia, Bulgaria.

Materials. Five differently microalloyed spheroidal graphite cast irons were studied. The reference material was spheroidal graphite cast iron without microalloyng (0 wt. % Sn content), and the other four materials were microalloyed by Sn

Table 1. Chemical composition (wt.%) of spheroidal graphite cast iron specimens

Element	Specimen designation				
	0	1	2	3	4
C	3.87	3.87	3.87	3.87	3.87
Sn	–	0.018	0.020	0.032	0.051
Si	1.55	1.55	1.55	1.55	1.55
Mn	0.34	0.34	0.34	0.34	0.34
P	0.029	0.068	0.063	0.075	0.077
S	0.012	0.051	0.059	0.047	0.060
Cr	0.030	0.030	0.030	0.030	0.030
Mo	0.018	0.019	0.020	0.017	0.018
Ni	0.024	0.024	0.024	0.024	0.024
Co	0.013	0.017	0.014	0.013	0.013
Cu	0.051	0.058	0.077	0.059	0.070
Ti	0.0013	0.0013	0.0018	0.0015	0.0013
W	0.126	0.126	0.135	0.123	0.126
Pb	0.039	0.039	0.043	0.040	0.039
As	0.036	0.036	0.037	0.038	0.040
Zr	0.003	0.003	0.003	0.003	0.003
B	0.0083	0.0083	0.0074	0.0091	0.0088

Table 2. Main mechanical properties (average values) of spheroidal graphite cast iron specimens

Specimen designation	Sn content (wt.%)	Yield strength (MPa)	Tensile strength (MPa)	Specific elongation (%)	Hardness HB
0	–	360	500	16	179
1	0.018	330	460	8.6	197
2	0.020	330	492	7.8	203
3	0.032	435	691	2.4	262
4	0.051	369	569	0.5	277

with the following wt. % Sn contents: 0.018, 0.020, 0.032 and 0.051. Table 1 shows the designation and chemical composition of the tested specimens.

The test specimens were produced from samples casted in ‘Osam’ factory in the city of Lovech (Bulgaria). Casting was done by using the ‘cover-bucket’ method. Metal melting includes two basic continuously controlled processes: melting and mixing. Details of the obtained castings, i.e. microstructures and mechanical properties, were described elsewhere[16–20]. The main mechanical properties of the specimens are presented in Table 2.

EXPERIMENTAL

TESTING RIG AND EXPERIMENTAL PROCEDURE

The experimental investigation of abrasive wear under vibration conditions, on the investigated specimens, was carried out on the pin-on-drum tribometer according to the standard test method for pin abrasion testing (ASTM G 132), in ambient air at room temperature (≈ 25°C). This tribometer has been modified in order to simulate the vibration conditions (periodically varying load). A schematic diagram of modified pin-on-drum tribometer is presented in Fig. 1.

The end of a studied specimen (3), with 17 mm in diameter, rotates about its axis and is positioned perpendicular to the impregnated corundum abrasive paper (5) with grain size of 46.2 μm (P320 grit). The abrasive paper (5) is fastened to and supported by a horizontal cylinder (2). The cylinder (2) rotates with constant angular speed about its horizontal axis. The motion of the specimen (3) is plane mo-

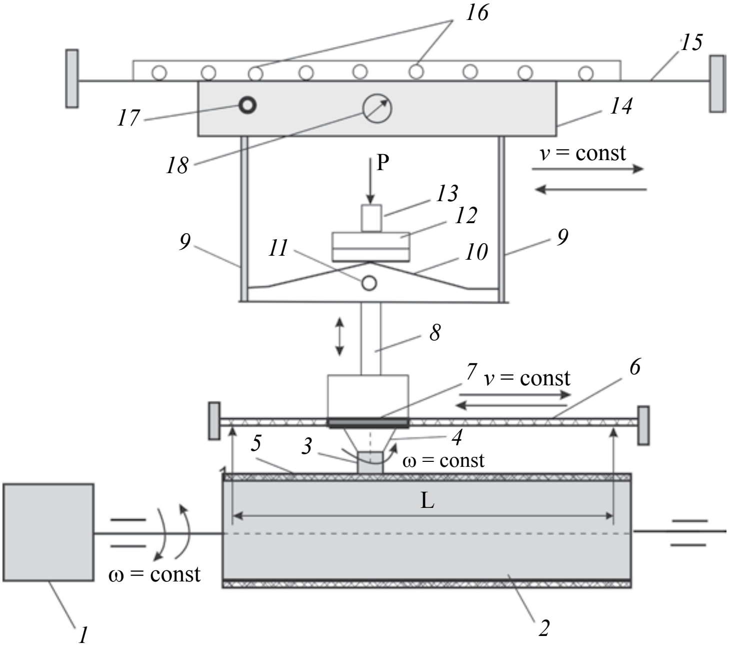

Fig. 1. Functional scheme of modified pin-on-drum tribometer used for the study of abrasive wear under the vertical vibrations
1 – AC motor; *2* – drum (horizontal cylinder); *3* – pin (specimen); *4* – loading block; *5* – abrasive surface (abrasive paper); *6* – static rack bar; *7* – gear ring; *8* – specimen fastening mechanism; *9* – vibrating frame; *10* and *11* – fixing mechanism; *12* and *13* – loading weights and loading mechanism; *14* – vibrator; *15* – vibrator supporting structure; *16* – vibrator driving mechanism; *17* – on/off button of the vibrator; *18* – regulator of vibrations parameters

tion: the apparent contact area translates on the generating line (generant) of the cylinder and at the same time rotates about its vertical axis. In a given moment of time, the points of the contact zone have various in value and direction velocities; however, in the process of contact interaction they change position periodically against the abrasive paper (5) fixed to the cylinder (2). This fact determines the homogeneous wear in all points of the contact area, which is the basic advantage of the device. Another advantage of the device is the aspect that the specimen comes always in contact with unused abrasive surface, where there is almost no wear debris. On one hand, this is the result of specimen's motion on helical line against the surface, and, on the other hand, the abrasive paper (5) is cleaned from the fine wear products by means of a vacuum pump. The stability of motion is provided by the constant ratio between the angular velocities of the drum and the specimen. The revolution direction of the cylinder, by switching on/off of the device is obtained by the control block.

Specimen (3) is fixed in the holder of the loading block (4) though elastic connection allowing self-regulation of the specimen to the abrasive paper (5) providing possibility for rotation around its own vertical axis. The loading block (4) engages the static rack bar (6) through the horizontal gear ring (7). Being parallel to the cylinder (2), the rack provides relative translation of the specimen on the generant of the cylinder. The specimen (3) is also fastened through the appliance (8) to the vibration frame (9), which provides vibrations from the vibrator (14) along the axis of the specimen. The normal central load P along the axis of the specimen is given through selection of appropriate weights (12) in the loading mechanism (13).

The vibrator (14) is mounted on the carrying structure (15), executing translational movement simultaneously with the vibration frame (8), the loading block (4) and the specimen (3) on the generant of the cylinder (2). Switch-on of the vibrator (14) is given by the button (17), and the vertical vibration velocity by the regulator (18). The vibration regulator (18) allows setting of various values of vibration velocity (w_z) in the interval $2.6 < w_z < 20$ mm/s. This interval is selected in accordance with the ISO standard for evaluation of vibration severity in machines and equipment[21].

Vibration parameters: vibration displacement (mm), vibration velocity (mm/s) and vibration acceleration (mm/s^2) are measured by the vibration meter PCE-VT 204 (Fig. 2a). Only the vibration velocity parameter is used and presented in this study. Table 3 shows the values of the vibration velocity in three directions (Fig. 2b): vertical (z axis), i.e. vertical vibration velocity (w_z), axial (y axis), i.e. axial vibration velocity (w_y) and horizontal (x axis), i.e. horizontal vibration velocity (w_x). Total vibration velocity is calculated as follows:

$$w=\sqrt{w_x^2+w_y^2+w_z^2} \tag{1}$$

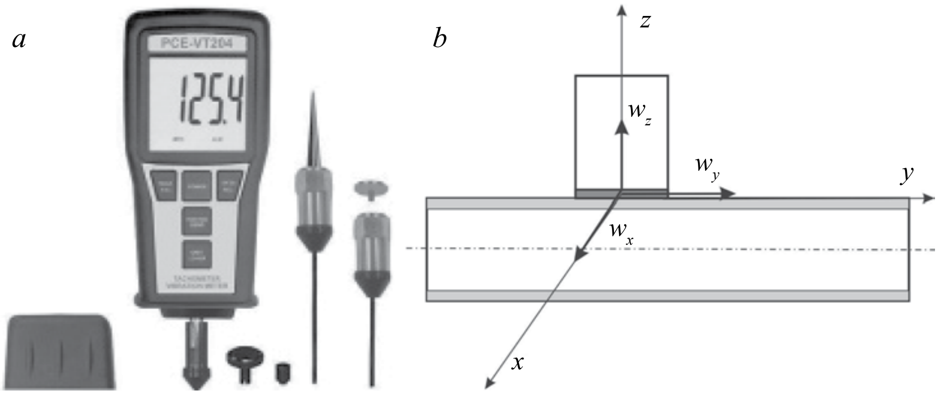

Fig. 2. Vibration measurements: *a* – vibration meter PCE-VT 204 and *b* – directions of the velocity components measurement

Table 3. Values of the vibration velocity components and total vibration velocity

Vibration velocity	Reference measures of the regulator				
	1	5	7	9	10
w_z (mm/s)	2.6	5.5	9.1	15.8	20
w_x (mm/s)	0.2	0.35	0.8	3.8	5
w_y (mm/s)	0.4	0.6	0.9	3.8	4.4
w (mm/s)	2.64	5.54	9.18	16.69	21.08

The procedure of study consists in mass loss measurement of each specimen at given values of vibration speed w_z and given identical values of: normal load $P = 3.92$ N, specimen cross-section area (assumed as a contact area) $A = 227$ mm^2, contact pressure $p = 0.02$ MPa, sliding distance $L = 24.5$ m, sliding speed $v = 0.31$ m/s, and impregnated corundum abrasive paper grit P320.

Following wear parameters were initially calculated: mass wear rate W_m in mg/m (Eq. 2), linear wear rate W_l in mm/m (Eq. 3), and linear wear resistance I in m/μm (Eq. 4).

$$W_\mathrm{m} = \frac{m}{L}, \tag{2}$$

$$W_\mathrm{l} = \frac{h}{L} = \frac{m}{L\rho A}, \tag{3}$$

$$I\,10^3 = \frac{1}{W_\mathrm{l}} = \frac{L}{h}, \tag{4}$$

where m is specimen mass loss in mg, h – specimen height loss in mm, and $\rho = 7.8$ mg/mm^3 is specimens density.

Both wear rates were calculated as a total wear rates, assuming that the steady-state wear was from the beginning of the tests (which is common thing for the abrasion wear). Linear wear rate were calculated since it is more convenient for engineering practice than mass wear rate. Linear wear resistance is calculated as a reciprocal value of the linear wear rate, and it represents the sliding distance for which the surface layer decreases by 1 μm.

RESULTS AND DISCUSSION

Experimental results for wear parameters for each specimen at various vibration velocities are given in Table 4.

Based on these results, appropriate diagrams are drawn for the dependences of wear rate on vertical vibration velocity w_z (Fig. 3) and the dependences of wear rate on tin (Sn) percentage content in the spheroidal graphite cast iron (Fig. 4).

The obtained experimental results show that the presence of normal vibration load increases the abrasive wear. Two regions (non-stationary and stationary) are observed in the relationships linear wear rate vs. vibration velocity for all speci-

Table 4. Wear parameters for different spheroidal graphite cast irons at various vibration velocities

Vibration velocity w_z (mm/s)	0	2.6	5.5	9.1	15.8	20
Specimen 0 (Sn = 0 wt. %)						
Mass loss *m* (mg)	41.3	90.1	102	131.8	136.9	143.7
Wear rate W_m (mg/m)	1.69	3.68	4.16	5.38	5.59	5.87
Wear rate W_l (mm/m)	9.52E-04	2.08E-03	2.35E-03	3.04E-03	3.16E-03	3.31E-03
Wear resistance *I* (m/μm)	1.05	0.48	0.43	0.33	0.32	0.30
Specimen 1 (Sn = 0.018 wt. %)						
Mass loss *m* (mg)	40.5	66.4	90.1	118	112.4	116.6
Wear rate W_m (mg/m)	1.65	2.71	3.68	4.82	4.59	4.76
Wear rate W_l (mm/m)	9.34E-04	1.53E-03	2.08E-03	2.72E-03	2.59E-03	2.69E-03
Wear resistance *I* (m/μm)	1.07	0.65	0.48	0.37	0.39	0.37
Specimen 2 (Sn = 0.020 wt. %)						
Mass loss *m* (mg)	38.4	50.8	76.5	92.4	75.4	96.8
Wear rate W_m (mg/m)	1.57	2.07	3.12	3.77	3.08	3.95
Wear rate W_l (mm/m)	8.85E-04	1.17E-03	1.76E-03	2.13E-03	1.74E-03	2.23E-03
Wear resistance *I* (m/μm)	1.13	0.85	0.57	0.47	0.58	0.45
Specimen 3 (Sn = 0.032 wt. %)						
Mass loss *m* (mg)	33.7	45.2	64.9	78.7	81.6	85.5
Wear rate W_m (mg/m)	1.38	1.84	2.65	3.21	3.33	3.49
Wear rate W_l (mm/m)	7.77E-04	1.04E-03	1.50E-03	1.81E-03	1.88E-03	1.97E-03
Wear resistance *I* (m/μm)	1.29	0.96	0.67	0.55	0.53	0.51
Specimen 4 (Sn = 0.051 wt. %)						
Mass loss *m* (mg)	28.3	33.1	43	57.5	58	85.1
Wear rate W_m (mg/m)	1.16	1.35	1.76	2.35	2.37	3.47
Wear rate W_l (mm/m)	6.52E-04	7.63E-04	9.91E-04	1.33E-03	1.34E-03	1.96E-03
Wear resistance *I* (m/μm)	1.53	1.31	1.01	0.75	0.75	0.51

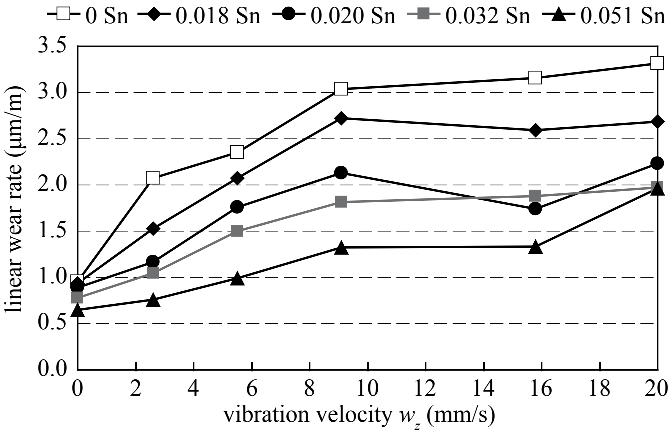

Fig. 3. Linear wear rate versus vertical vibration velocity w_z by cast irons with various tin (Sn) content

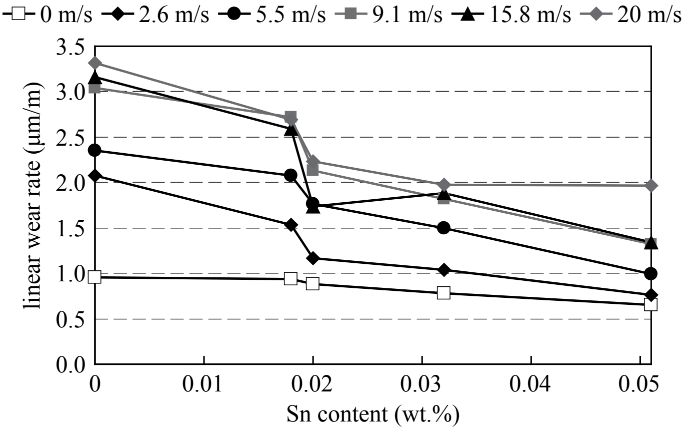

Fig. 4. Linear wear rate versus tin (Sn) content at various vertical vibration velocities

mens (Fig. 3).

In the non-stationary region ($w_z < 9.1$ mm/s) a linear increase of wear rate is noticed. On the other hand, in the stationary region ($w_z \geq 9.1$ mm/s) wear rate is almost constant, and the assumption is that the further increase of vibration would not have some significant influence. In order to perceive the influence of vibra-

Table 5. Approximate influence of the vibration velocity on wear resistance

Specimen designation	Wear resistance at $w_z = 0$ mm/s (m/μm)	Wear resistance at $w_z \geq 9.1$ mm/s (m/μm)	Relative wear resistance
0 (Sn = 0 wt. %)	1.05	0.32	3.32
1 (Sn = 0.018 wt. %)	1.07	0.38	2.85
2 (Sn = 0.020 wt. %)	1.13	0.50	2.27
3 (Sn = 0.032 wt. %)	1.29	0.53	2.43
4 (Sn = 0.051 wt. %)	1.53	0.67	2.29
		Average	2.63

Table 6. Approximate influence of the Sn wt. % content on relative wear resistance

Specimen designation	Vibration velocity w_z (mm/s)						Average relative wear resistance
	0	2.6	5.5	9.1	15.8	20	
0 (Sn = 0 wt. %)	1	1	1	1	1	1	1
1 (Sn = 0.018 wt. %)	1.02	1.36	1.13	1.12	1.22	1.23	1.18
2 (Sn = 0.020 wt. %)	1.08	1.77	1.33	1.43	1.82	1.48	1.48
3 (Sn = 0.032 wt. %)	1.23	1.99	1.57	1.67	1.68	1.68	1.64
4 (Sn = 0.051 wt. %)	1.46	2.72	2.37	2.29	2.36	1.69	2.15

tions, a relative wear resistance is calculated (Table 5). It is calculated by dividing the wear resistance without vibrations and wear resistance in the stationary region ($w_z \geq 9.1$ mm/s). The results show that the wear resistance is approximately 2.63 times lower in the presence of the vibration with velocities higher than 9 mm/s.

Presence of tin (Sn) in the spheroidal graphite cast iron reduced wear rate, i.e. increase wear resistance (Fig. 4). Higher Sn wt. % content generally induces higher wear resistance. For all specimens, a sudden decrease of wear rate was noticed at 0.020 wt. % Sn. In order to perceive the influence of Sn wt. % content, a relative wear resistance is also calculated (Table 6). This relative wear resistance was calculated by taking the wear resistance of the specimen without microalloyng (0 wt. % Sn content) as a reference (its relative wear resistance is equal 1). From Table 6 can be noticed that the wear resistance is approximately 2.15 times higher in the presence of 0.051 wt. % Sn comparing it with the specimen without microalloying.

Fatigue processes resulting from the micro-impacts and the micro-cutting by the abrasive particles are the basic wear mechanisms in tribosystems with high vibrations. Increasing vibration velocity leads to increase of the number of micro-contacts and the real contact area in a unit time of the contact interaction.

Metallographic studies in the case of abrasive wear without vibration have shown a uniform process of surface destruction without fatigue breakings (the values of the wear rate are more close to each other, (Fig. 3)). In the presence of vibrations, cracks appear in the boundary contact zones between the graphite grains and the matrix where the process of destruc-

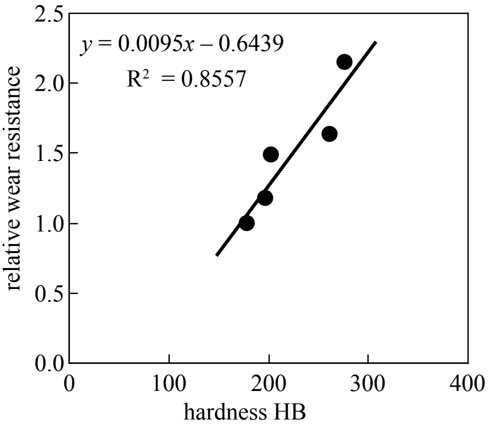

Fig. 5. Relative wear resistance versus hardness

tion begins. Areas of plastic deformation are observed in those boundary zones. In the case of abrasive wear with vibration, the process of plastic deformation is accelerated, and the shift and outlet of the dislocations are facilitated[3]. This process depends on the composition and the microstructure of the spheroidal graphite cast iron. The microalloying with Sn in the studied percentage interval results in increment of the pearlite phase in the matrix keeping the spheroidal shape of the graphite[16–20]. The increase of the wear resistance with Sn content increment is due to the hardness increase resulting from the pearlitization of the matrix (Fig. 5).

CONCLUSIONS

The paper considers a comparative study of wear characteristics of spheroidal graphite cast irons without and with various wt. % Sn microalloying under conditions of abrasive wear with vibration load. Experimental results are obtained for the dependence of the wear rate on the normal vibration velocity and the percentage of Sn content.

Two regions in the variation of wear with the vibration velocity are established: non-stationary region by vibration speeds $0 < w_z < 9.1$ mm/s and stationary region by vibration speeds $9.1 \leq w_z \leq 20$ mm/s. The wear resistance is approximately 2.63 times lower in the presence of the vibration with velocities higher than 9 mm/s.

Increase of Sn percentage in the spheroidal graphite cast iron reduces wear rate, i.e. increases wear resistance, almost linearly. The wear resistance is approximately 2.15 times higher in the presence of 0.051 wt. % Sn comparing it with the specimen without microalloying.

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