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ON THE USE OF ACOUSTIC EMISSION TO ASSESS THE WEAR IN A TRIBOSYSTEM

Key words: tribosystem, DLC coating, sound, regression trees.

Abstract: The article focuses on the analysis of acoustic emission signals generated under dry sliding friction conditions. Two tests were conducted using a TRB[3] tribometer with the disc made of 100Cr6 steel with a DLC coating, and pin made of corundum (Al_2O_3) and steel 100Cr6, respectively. Two tests with the disc without DLC coating were also carried out. The audio data written in the 16-bit linear pulse-code modulation (LPCM) format were analysed using the SpectraPLUS software. An A-weighting filter and 1/1 and 1/3-octave band filters were used for sound level measurements.
The analysis of the equivalent sound level calculated for 10-second time intervals was carried out. The highest A-weighted sound level occurred during the first 2 hours of the test with the disc having a DLC coating and pin made of 100Cr6 steel. At the end of this test, the sound level dropped by about 40 dB compared to the maximum. The lowest A-weighted sound level was recorded during the last 2 hours of the test with disc having a DLC coating and pin made of corundum.
The time-dependent variability of sound parameters was predicted using the regression tree and random forest models, which proved to be accurate and easy to follow.

Ocena emisji akustycznej w procesie zużycia elementów systemu tribologicznego

Słowa kluczowe: system tribologiczny, dźwięk, powłoka DLC, drzewa regresji.

Streszczenie: W pracy przedstawiono analizę dźwięku zarejestrowanego podczas tarcia technicznie suchego w ruchu ślizgowym. Dwa testy przeprowadzono na tribometrze TRB[3] dla próbek wykonanych ze stali 100Cr6 z powłoką DLC i przeciwpróbek wykonanych odpowiednio z korundu (Al_2O_3) i stali 100Cr6. Przeprowadzono również dwa testy dla próbek bez powłoki DLC. Dźwięk został zarejestrowany w standardzie 16-bitowego liniowego PCM, a następnie poddany analizie w programie SpectraPlus. Dla kolejnych chwil czasu wyznaczono wartości poziomu dźwięku A, a także poziomy dźwięku w wybranych pasmach oktawowych i 1/3-oktawowych.
Przeprowadzono analizę równoważnego poziomu dźwięku obliczonego dla 10-sekundowych odcinków czasu. Najwyższy poziom dźwięku A występował podczas pierwszych 2 godzin testu próbki z powłoką DLC i przeciwpróbki wykonanej ze stali 100Cr6. Pod koniec tego testu poziom dźwięku spadł o około 40 dB względem dotychczasowego maksimum. Najniższy poziom dźwięku A zanotowano podczas ostatnich 2 godzin testu, w którym próbka miała powłokę DLC, a przeciwpróbka była wykonana z korundu. Utworzono modele opisujące zmienność w czasie wybranych parametrów dźwięku, oddzielnie dla każdej próbki. Do utworzenia modeli zastosowano drzewa regresji oraz Random Forest. W pracy zamieszczono analizę dokładności i przejrzystości otrzymanych modeli.

Introduction

In tribological systems, energy required to overcome the resistance attributable to friction can be dissipated, transformed, or accumulated [1]. One of the phenomena occurring during friction is acoustic emission. Vibration and noise generated during the stick-slip friction in an instrument panel was investigated in [2]. The effect of fluid film lubrication on the attenuation of noise and the vibration of the gear mesh was discussed in [3]. The effect of grooves on the emission of 1–20 kHz sounds was analysed in [4]. The impact of windscreen waviness on the emission of the sound of the above-mentioned frequencies during wiper blades work was investigated in [5]. The influence of selected factors on the emission of sound caused by friction, as well as sound frequency analysis at various stages of tribotests was studied in [6]. This article presents original research and focuses on the analysis of sound generated under dry sliding friction conditions.

1. Materials and methodology

Tribological tests (Table 1) were performed on ball-on-disc tribometer (Figure 1). The balls with a diameter of 6 mm were made of 100Cr6 steel and aluminium (III) oxide – Al_2O_3, while the rotating discs with a diameter of 42 mm and a height of 6 mm were made of 100Cr6 steel with or without a DLC coating. All tests were conducted under conditions of technically dry friction. The sliding distance was 1000 m.

Table 1. Parameters of tribological tests

Parameter	Unit	Value
Load	N	10
Sliding rate	m/s	0.07
Sliding distance	m	1000
Relative humidity	%	55 ± 5
Ambient temperature	°C	25 ± 1

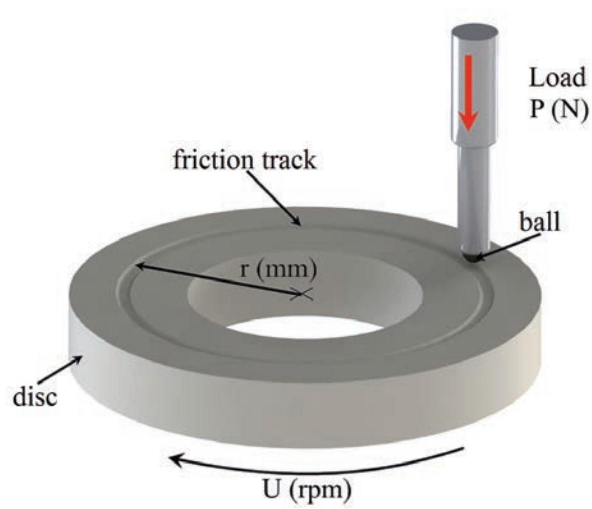


Fig. 1. Schematic of friction node used in tests

Tested material pairs are shown in Table 2, using the following notation: Test 1 for disc and a ball made of 100Cr6 steel, Test 2 for disc made of 100Cr6 steel and a ball made of Al_2O_3, Test 3 for disc with a DLC coating and a ball made of Al_2O_3, and Test 4 for disc with a DLC coating and a ball made of 100Cr6 steel. Material pairs were selected because they are widely used in maintenance technology.

Table 2. Materials used in tribological tests

Test	Disc	Ball
Test 1	100Cr6 steel	100Cr6 steel
Test 2	100Cr6 steel	Al_2O_3
Test 3	with DLC coating	Al_2O_3
Test 4	with DLC coating	100Cr6 steel

Properties of selected materials are shown in Table 3 (100Cr6 steel and Al_2O_3) and in Table 4 (DLC coating compared with diamond).

Table 3. Mechanical properties of 100Cr6 steel and Al_2O_3 [13, 14]

Material	Young's modulus E [GPa]	Tensile strength R_m [MPa]	Compressive Strength [MPa]	Hardness [Vickers]	Density [g/cm^3]
Steel 100Cr6	243	520	454	210	7.83
Al_2O_3	393	206–300	2070–2620	1365	3.987

Table 4. Mechanical properties of diamond and a-c:h-type dlc coating [15]

Material	Young's modulus E [GPa]	Form	Covalent bonds	Hardness [GPa]	Density [g/cm^3]
a-C:H	100–300	Films	Intermediate sp^3	10–30	~2.2
Diamond	1000	Bulk, films	100% sp^3	100	~3.5

During the tests, sound was registered by a Linear PCM Recorder Olympus LS-P1 in such a way that the analogue audio signal was sampled with 44100 Hz frequency and stored in digital 16-bit linear PCM (pulse-code modulation) format. Then, SpectraPlus SC software [7] applied A-weighting [12] to the recorded digital audio signal. Later, using the same software, the RMS (root mean square) level of the A-weighted signal was determined for each 1-second time period, and denoted by $L_{A,i}$. The obtained $L_{A,i}$ values were expressed in decibels full-scale (dBFS) [8]. In the next step, the RMS level of the A-weighted audio signal for each 10-second time period, denoted by L_A and expressed in dBFS, was calculated using Equation (1) for equivalent sound level [9]:

$$L_A = 10\log\left(\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{A,i}}\right) \tag{1}$$

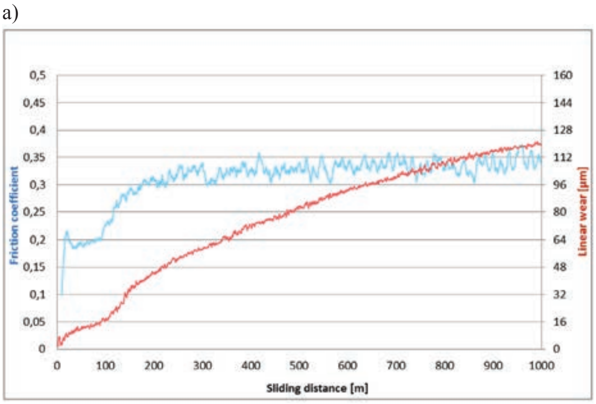
where $L_{A,i}$ values come from 10 consecutive seconds, and N equals 10.

During selected tests, equivalent sound level A (A-weighted), as well as sound levels in each 1/3-octave bands, for 100-millisecond time periods were measured using a Class 1 digital sound level meter and analyser SVAN971.

2. Results and discussion

Figure 2 shows the course of the friction coefficient and linear wear as a function of sliding distance for tribological tests marked in Table 2 as Test 1 and Test 2. In both tests, the disc was made of 100Cr6 steel, and the ball was made of 100Cr6 steel and Al_2O_3, respectively.

a)



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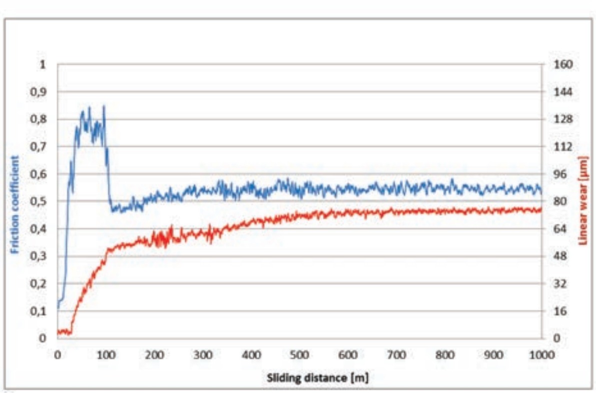
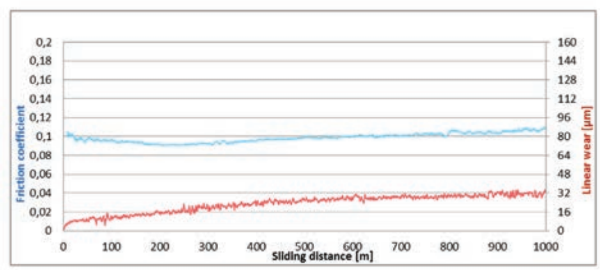


Fig. 2. The friction coefficient and linear wear in tribological tests: a) Test 1, b) Test 2

The results of Test 1 indicate that the friction coefficient reaches values below 0.25 during the first 100 meters, and then remains between 0.3 and 0.4. On the other hand, in Test 2, the friction coefficient reaches values exceeded 0.8 during the first 100 meters, and then decreased and maintained values between 0.45 and 0.6.

Figure 3 shows the course of the friction coefficient and linear wear as a function of sliding distance for tribological tests marked in Table 2 as Test 3 and Test 4. In both tests, the disc was coated with a diamond-like carbon coating (DLC), and the ball was made of Al_2O_3 and 100Cr6 steel, respectively. The friction coefficient for all of Test 3 was close to 0.1, while, in Test 4, it was about 0.35 for the first 300 meters and about 0.2 for the last 400 meters.

a)



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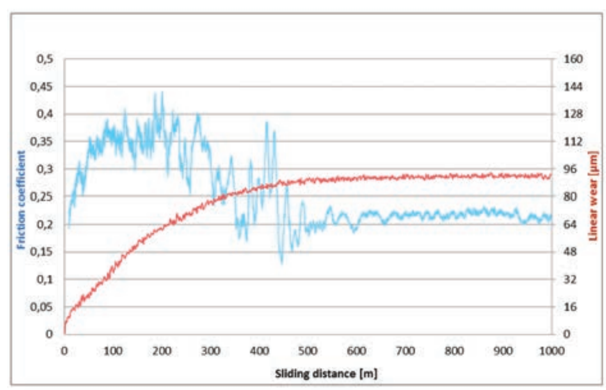

Fig. 3. The friction coefficient and linear wear in tribological tests: a) Test 3, b) Test 4

Figure 4 shows the surface texture of the disc formed during Test 2. In Figure 4b, the effects of the transport and deposition of material on the sides of friction path are visible. In all conducted tests, there is a correlation between friction coefficient and L_A values or high frequency sound emission. Figures 5 and 6 present L_A values as a function of sliding distance in tribological tests: Test 1, Test 2, Test 3, and Test 4.

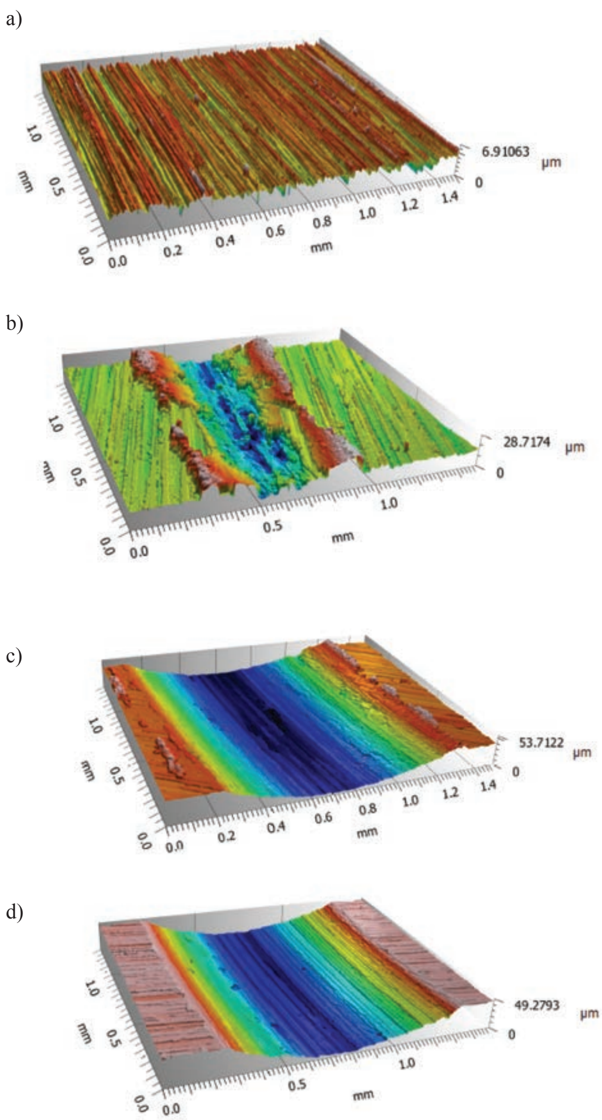

Fig. 4. Surface texture formed during Test 2: a) before friction, b) near the maximum of friction coefficient, c) at sliding distance of 300 m, d) at the end of the test

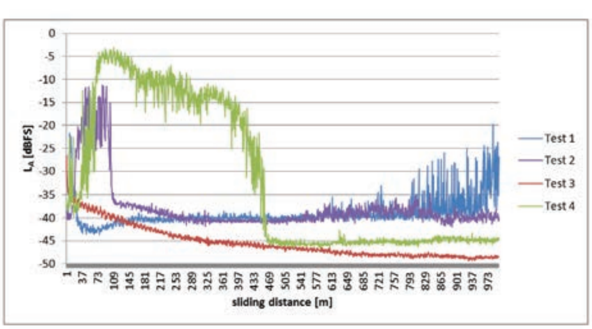

Fig. 5. L_A values during tribological tests from Table 2

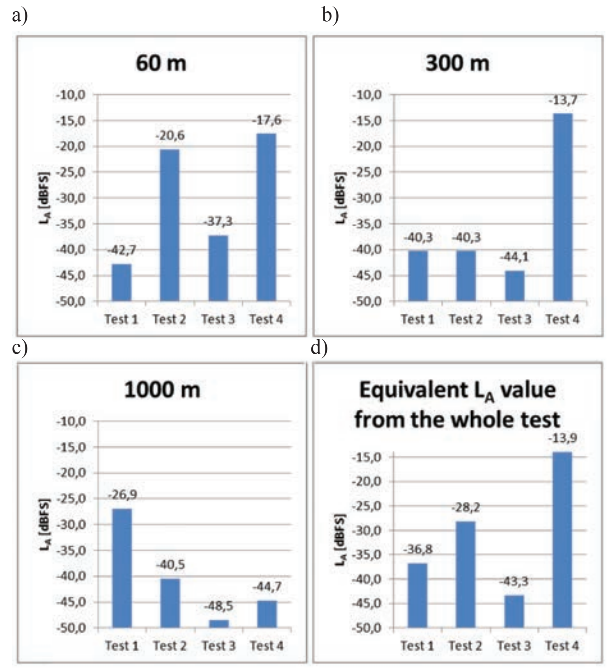

Fig. 6. L_A values during tribological tests from Table 2: a) at 60 m, b) at 300 m, c) at 1000 m of sliding distance, d) equivalent value for the whole test, calculated using Equation (1) not for N = 10, but N = 15250

The highest L_A values were at 60 m, 300 m, and these levels were reached throughout Test 4. However, at 1000 m of sliding distance, the L_A values are low in all tests except Test 1.

3. Model of sound level variability

The set of L_A values calculated by Equation (1) for 10-second time periods in Test 1 were used as the training dataset for the RandomForest algorithm [10] (random forest of regression trees) implemented in the Weka software package [11]. The obtained model (Figure 7) has very good accuracy on the training dataset

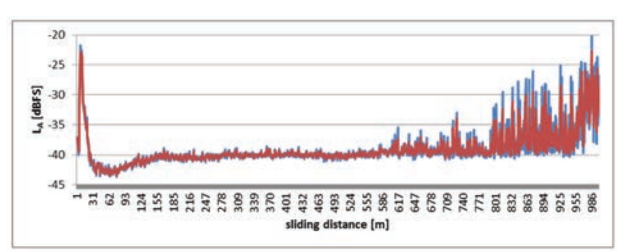

Fig. 7. L_A values during tribological Test 1: calculated from measurement (blue), and calculated by RandomForest model (red)

– root mean square error (RMSE) is 0.73 dB. However, accuracy is lower (RMSE equal to 1.94 dB) when tested by the 10-fold cross validation method. In this method, the whole dataset is divided into training (90% of data) and validation (10% of data) datasets, and the model is obtained. This process is repeated 10 times. Total accuracy is calculated as an average of accuracies of all 10 models on 10 respective validation datasets. The obtained RandomForest model of L_A variability can be used in practical technical applications.

The regression tree model of L_A variability, obtained using Weka and the same training dataset as for RandomForest, has slightly better accuracy (RMSE equal to 1.85 dB) when tested by 10-fold cross validation.

Conclusions

The emission of sound depends on phenomena and processes occurring in the friction node, which depends on the material pair used in dry sliding friction conditions. The highest L_A values were observed during the first 2 hours of Test 4 (the tribosystem consisting of DLC and 100Cr6 steel). The lowest L_A values were observed during Test 3 (the tribosystem consisting of DLC and Al_2O_3). The RandomForest method allows one to build the model of variability of sound levels as a function of sliding distance in a given tribological test.

When observing changes in the friction coefficient and linear wear, one can notice their correlation with sound emission. It is also possible to distinguish between material pairs on the basis of emitted sound. The observation of sound emission allows the monitoring the work of tribosystem and avoiding damages.

Future research will include the construction of classifiers for distinguishing between various material pairs, as well as classifiers for detecting the stage of wear.

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