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The application of the computer image analysis in wear particle research

K e y w o r d s

Wear mechanisms; wear particle analysis, lubricating oils, computer image analysis.

S ł o w a k l u c z o w e

Mechanizmy zużywania, analiza cząstek zużycia, oleje smarowe, komputerowa analiza obrazu.

S u m m a r y

In this research, the possibilities of characterising the texture, colour and contour of wear particles were investigated. The assessment of the texture and colour of wear particles on the basis of the analysis of changes in the grey-scale and individual components of the colour model CIE L*a*b* was performed. For a statistical description of distributions, the following parameters were used: the averages grey-level and the values of maximal and minimal grey-level. The assessment of the surface texture and contour of wear particles by the Fourier and fractal analyses was also carried out. The amplitude spectrum numerical parameters for chosen lines marked on the particle image were determined with the help of one dimension Fast Fourier Transformation (FFT). Based on the suitably prepared data obtained from images, the fractal dimension of the contour of the investigated particles, using the compass method, was determined. The usefulness of the determined parameters was evaluated by determining the wear particles' affiliation to the suitable

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type. The correlation between morphological features of wear particles and mechanisms taking place during friction couple wear was determined on the basis of an analysis of the obtained research results of individual groups of wear particles.

1. Introduction

As the result of the operation of the tribological processes taking place in friction couples of machines and devices, the wear products, being metal particles or their oxides, appear. The features and quantities of these products are determined by the properties of the surface layers of the cooperating tribological elements, exploitation conditions, the quality of the lubricating substance, and its tribological properties. Empirical correlation between different features of wear particles and wear mechanisms can be used as basis for the identification of particle types and the determination of the wear mechanism, providing an assessment of the state of friction couples [1]. The application of computer image analysis enables conducting the comprehensive assessment of wear particles on which it is possible to base friction couple diagnosis [1-13].

The aim of work was to determinate the morphological features of wear particles obtained in laboratory tribological tests.

2. Materials and methods

For the purpose of obtaining the particles, the tribological testers, prod. ITeE – PIB in Radom were applied [14]. The construction of the friction couples and their conditions of movement were taken into consideration in choosing the testers. The tests were conducted under conditions of adhesive, scuffing, abrasive, and fatigue wear.

Tests of adhesive and abrasive wear were performed using the apparatus T-01 M. The pin with 3 mm diameter was made of LH 15 steel, having a hardness of 60 HRC. The disc with a 45 mm diameter was made of 45 steel, having a hardness of 30 HRC. Three different loads 10, 30, and 50 N, were employed, the sliding speed used was 0.5 m/s, and the friction distance was 500 m. The test lasted 1000 s.

For the conducting of fatigue wear test (under oscillatory sliding conditions) the apparatus T-19 was used. The disc used for the test was 25 mm in diameter and the ball was 10 mm in diameter. Both the disc and ball were made of LH 15 steel with a hardness of 60 HRC. The test parameters were as follows: loads 50 and 100 N, the amplitude of movement = 0.6 mm, and the frequency of oscillation = 50 Hz. Friction was performed under unlubricated conditions. The test was 10 min in duration.

The scuffing wear test was carried out using a four-ball tester T – 02 in accordance with standard PN–76/C–04147. It involved conducting 10–second runs of the set of four balls under a gradually increasing load in presence of an investigated lubrication product until welding signs occurred. In the test, ½" diameter steel balls of hardness 60 HRC and surface roughness of 0.32 μm (R_a) were used, and the lubricant was SN 400 base oil.

Preparation of the particles provided involved isolating them from the lubrication medium through ultrasonic rinsing and filtration for research.

The wear particles images were recorded and stored for further analyses with the use of a commercial system of computer image processing and analysis - Computer Scanning Systems Ltd. prod. Poland equipped with the following:

- MM-40 microscope model L3FA prod. Nikon;
- A digital optical camera, Industrial Colour CCD Camera, model GP-KR222E prod. Panasonic;
- Indeo fast Frame Grabber card; and
- IBM PC class computer with Pentium processor, Windows XP operating system and software for analysis of microscopy images Multiscan v. 14.02.

The source of light in the light microscope was a halogen light bulb giving a colour temperature around 3000 ^{o}C. The images were recorded using reflected light illumination for revealing the details of their surface and colour. To improve the depth of sharpness, the images were registered with a partially closed diaphragm. The reduction of reflection was achieved through the possibility of the adjustment of the setup of the diaphragm. The image magnifications used during registration were 500, 200 and 50, depending on the size of the particles. For conducting measurements, the system was defined and calibrated according to model image and measurement unit.

For the research of images with the use of colour model L*a*b*, one of several known programs was chosen for graphic processing of the bitmap images with Adobe Photoshop. This program offers the possibility of displaying a histogram of the distribution of grey-scales in individual colour channels and the global grey-scale for a given area. It allows one to perform measurements on registered digital images; therefore, it realises some tasks of digital image analysis. The histogram window presents the distributions of component colours, which are not standard values. Transformation of data is possible according to the following formulas:

$$L^* = \frac{L}{255} \times 100 \qquad (1)$$

$$a^* = \frac{240a}{255} - 120 \qquad (2)$$

$$b^* = \frac{240b}{255} - 120 \tag{3}$$

Where:

- L,a,b – components displayed in histogram window with values from 0 to 255,
- L^* – achromatic component normalised to the range (0, 100), contains information concerning image luminance,
- a^* – chromatic component normalised to the range (-120, 120), contains information about colours from green to red,
- b^* – chromatic component normalised to the range (-120, 120), contains information about colours from blue to yellow.

The one dimensional Fast Fourier Transformation (FFT) contained in the Multiscan program was used for the realisation of texture analysis. The texture research of wear particles was performed by carrying out Fourier analysis for points of chosen lines marked on the particle image. The positions and lengths of the measuring lines were dependent on the dimensions and shapes of investigated particles. In order to assure the comparability of results for all particles, the same number of elements of input series n equal to 32 was accepted. Results of successive measurements were recorded in text files for utilisation in further analyses.

For analysis of contour algorithm contained, the program Multiscan was used. Fractal dimensions of the contours of investigated particles were obtained by using the chord method. Fractal analysis of particles involved the replacement of their contour by a broken line with apexes tangent to a contour and constant length side. The procedure was repeated for all chosen lengths of a side. Calculated values were the basis for plotting the dependence of the logarithm of the broken length from the logarithm of length of the side in the form of a linear regression equation.

In conducting the research, the number of analysed images of individual types of particles was 10 or 5, depending on method of research. This number of particles was necessary to obtain a useful result during the simultaneous limitation of times of the research.

3. Discussion of research results

The research included the assessment of the colours, textures, and contours of wear particles. As a result of the analysis of the series of particles, related to the components in the CIE L*a*b* colour model, Fourier coefficients and fractal dimension were determined.

4. L *, a*, b* colour components

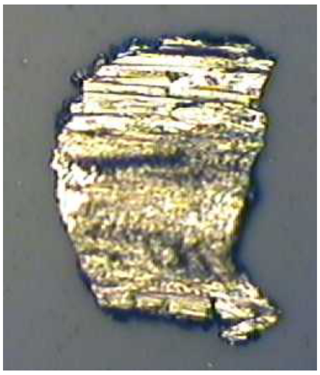
The results of the colour analysis of the investigated wear particles in the CIE L*a*b* system are presented in Table 1. Data concern 10 particles of each kind. The analysis the colours of wear particles indicated differences in the brightness of individual types of particles. Each type of particle is represented on a histogram (Figs. 1 and 2) by bands placed in certain characteristic areas of the changes of lightness, which allows for their classification. The lowest values of lightness were found for the following wear particles: adhesion under load of 10 N, abrasion and scuffing under load of 1000 N (L^* = 34.41, 40.59 and 40.64, respectively). The highest values were for the following wear particles: scuffing under load of 500 N and adhesion under load of 30 N (L^* = 63.78 and 57.13, respectively). A good indicator of the differences between the investigated types of wear particles are also the values of a^*. In the case of wear particles, with scuffing under a load of 1000 N and abrasion, the average value of the a^* component was negative, indicating the presence of green colour. In all remaining cases, positive values of a^* component were found, which in turn indicates the presence of red colour. For fatigue wear particles, the numerical values of this parameter were respectively, 9.23 under load of 100 N, and 6.25 under load of 50 N, which proves a relatively high share of this colour. The range of changes of a^* values suggests that the green component was also present in other particle types. The b^* component showed negative values for adhesive, abrasive, and fatigue wear particles, while adhesive wear particles under load of 10 N (b* = -11.83) were characterised by the highest degree of blue colour saturation. However, the highest saturation of yellow colour was observed for scuffing wear particles under a load of 500 N (b^* = 8.73). The obtained results indicate the usefulness of the L*a*b* model in research for the purpose of the identification of particle colours. It solves the problem of differences in colour reproduction resulting from use of various devices. Through the introduction of quantitative estimation and the elimination of subjective factors during research, the described method should lead to correct and exact identification of particle types. The other statistical parameters describing colour such as standard deviation, skewness, and kurtosis can be also subjected to estimation. When making a choice of the most effective parameters, it is possible to apply advanced methods of data analysis, e.g. PCA method.

Table 1. Average, minimal and maximal values L*, a* ,b* of wear particles
Tabela 1. Wartości średnie, minimalne i maksymalne L*, a* ,b* cząstek zużycia

.No.	Wear particles type	Statistic parameters	L*	a*	b*
1.	Adhesive wear particles – load 10 N	Min. - Max.	28.18 – 49.78	-3.95 – 3.76	-17.56 - -2.46
		Average value	34.41	1.73	-11.83
2.	Adhesive wear particles – load 30 N	Min. - Max.	38.26 – 75.62	-2.55 – 2.00	-16.20 - 2,42
		Average value	57.13	0.05	-4,4
3.	Adhesive wear particles – load 50 N	Min. - Max.	31.02 - 67,74	-1.04 – 1.84	-15.98 – 5.66
		Average value	47.80	0.34	-5.71
4.	Scuffing wear particles – load 500 N	Min. - Max.	49.16 – 78.98	-1.06 – 1.67	-3.68 – 15.12
		Average value	63.78	0.02	8.73
5.	Scuffing wear particles – load 1000 N	Min. - Max.	32.95 – 65.65	-3.43 – 4.29	-5.98 – 22.83
		Average value	40.64	-1.17	0.84
6.	Abrasive wear particles – load 30 N	Min. - Max.	33.19 – 46.52	-2.73 - -0.71	-10.03 - -2.78
		Average value	40.59	-1.46	-6.12
7.	Fatigue wear particles – load 50 N	Min. - Max.	46.01 – 56.30	4.14 – 9.36	-15.40 – 0.17
		Average value	52.33	6.25	-8.5
8.	Fatigue wear particles – load 100 N	Min. - Max.	48.76 – 64.58	3.69 – 14.25	16.08 – 10.89
		Average value	54.63	9.23	-3.29

The extreme values were obtained based on 10 particles.

a)



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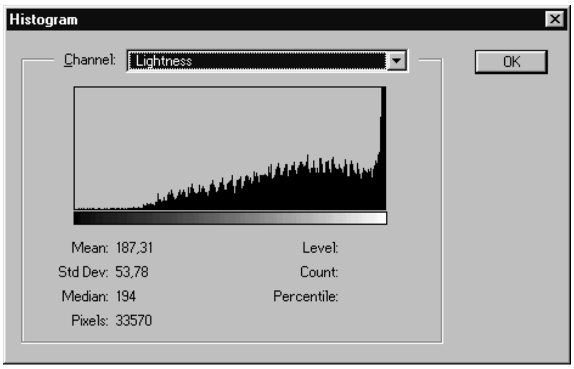

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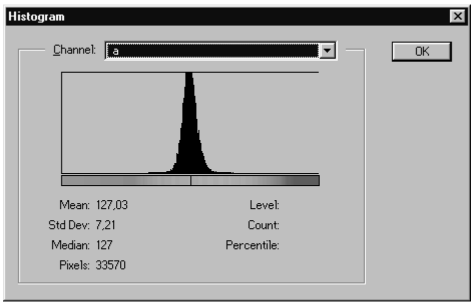


d)

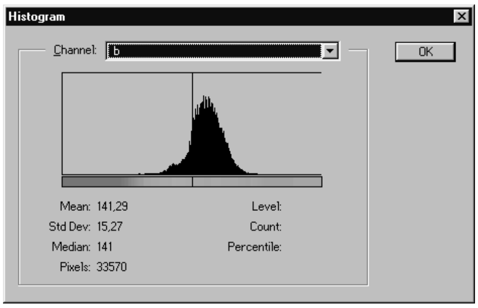
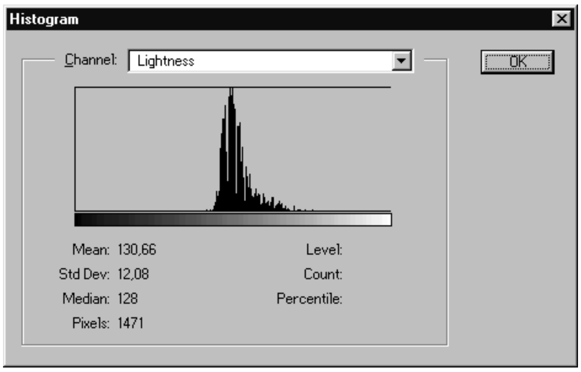


Fig. 1. Image of a scuffing wear particle under contact load of 500 N (a) and histograms of grey levels (b) and components a (c) and b (d)
Rys. 1. Obraz cząstki zużycia scuffingowego przy obciążeniu styku 500 N (a) oraz histogramy jasności (b) i składowych: a (c) i b (d)

a)

b)



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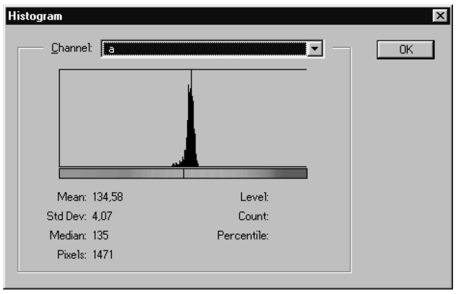

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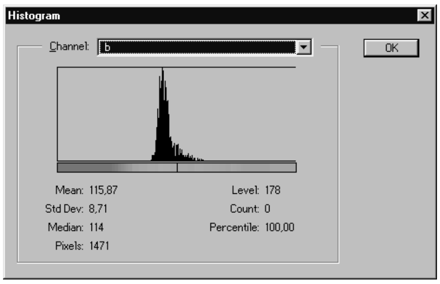
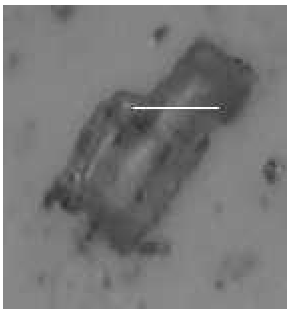


Fig. 2. Image of a fatigue wear particle under contact load of 100 N (a) and histograms of grey levels (b) and components a (c) and b (d)
Rys. 2. Obraz cząstki zużycia zmęczeniowego przy obciążeniu styku 100 N (a) oraz histogramy jasności (b) i składowych: a (c) i b (d)

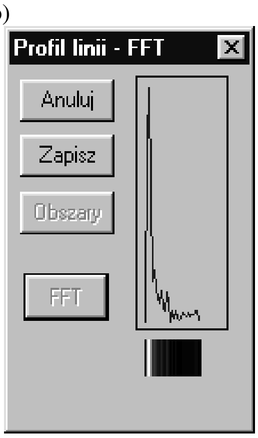
5. Fourier coefficients

In Fig. 3, an example of the amplitude spectra, obtained for adhesive wear particles, is presented. On the images of these particles, segments subjected to analysis are marked by a continuous line. On the abscissae axis of the spectrum diagram are located the successive harmonic components (n = 32), and the ordinate's axis presents the values of spectra in the form of brightness levels from range of 0 – 255. The average values of the harmonic components for the chosen five wear particles of each kind are shown in Fig. 4 and Table 2. The number of harmonic components has been limited from 32 to 16, in which the whole or part of the spectrum power is concentrated.

a)



b)



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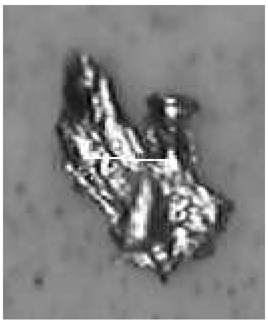

d)

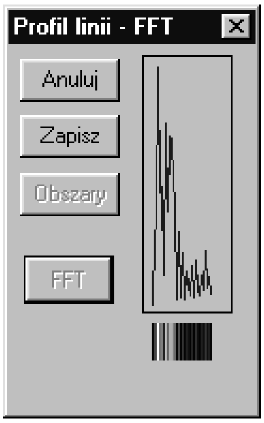

Fig. 3. Images of the adhesive wear particles under contact load of 10 (a) and 50 N (c) and correspond to them Fourier amplitude spectra (b) and (d)
Rys. 3. Obrazy cząstek zużycia adhezyjnego przy obciążeniu 10 (a) i 50N (c) i odpowiadające im fourierowskie widma amplitudowe (b) i (d)

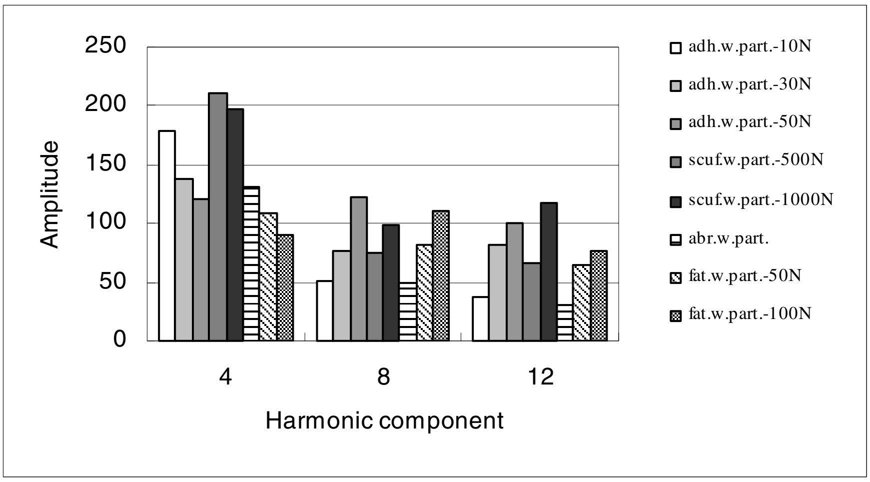

Fig. 4. The graph of the harmonic amplitudes for lines marked on the particles' surface
Rys. 4. Wykres amplitud składowych harmonicznych odcinków zaznaczonych na powierzchni cząstek

The analysis of the harmonic components of the amplitude spectrum for chosen types of wear particles has shown that, in case wear particles, adhesion under a load of 10 N, and abrasion, the levels of second, third, and fourth harmonic component are higher than the level of other harmonics, which shows that image includes a smooth transition without violent changes in the levels of brightness. The other situation occurred for wear particles for fatigue, and adhesion, under loads of 30 and 50 N, and scuffing, where the levels of several further harmonics are distinctly higher. The spectra of adhesive wear particles, under a load of 50 N, and scuffing wear particles, under a load of 1000 N, differ from the remaining particles in higher levers of harmonics typical for more complex textures. For example, the twelfth component of wear particles, adhesion under load of 50 N and scuffing under load of 1000 N, is 100 and 118, and the remaining particles are in a range from 64 to 82.

The numbers in parentheses are the standard deviation values for five particles.

The majority of the analysed harmonic components are characterised by the high variability within each kind of particle. Generally, considering standard deviation values shown in the comparisons, one should regard them as large. It also shows the coefficient of variation values (relative deviation standard), which is from 14 to 93% for dominant harmonic components and from 22 to 78% for the remaining harmonics. On account of variety of features of the considered image and the possibility of the occurrence of deformation and noise, the methods of automatic classification of spectra can be use for further analysis of the variability of measurement data.

Table 3. Average values of harmonic components of wear particles amplitude spectra
Tabela 3. Wartości średnie składowych harmonicznych widm amplitudowych badanych cząstek zużycia

No.	Wear particle type	Component number															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Adhesive wear particles – load 10 N	0	158 (58)	214 (56)	178 (98)	79 (58)	80 (52)	90 (51)	51 (38)	55 (42)	63 (11)	36 (25)	38 (14)	23 (16)	24 (8)	22 (11)	14 (4)
2	Adhesive wear particles – load 30 N	0	215 (51)	183 (59)	138 (55)	166 (75)	131 (104)	109 (101)	76 (34)	100 (60)	45 (14)	84 (33)	82 (62)	57 (35)	76 (40)	57 (30)	64 (32)
3	Adhesive wear particles – load 50 N	0	186 (82)	222 (62)	120 (17)	112 (60)	146 (67)	110 (94)	123 (94)	142 (90)	84 (32)	83 (38)	100 (72)	83 (62)	63 (45)	54 (32)	47 (36)
4	Scuffing wear particles – load 500 N	0	159 (60)	174 (48)	211 (65)	137 (44)	116 (67)	83 (50)	75 (47)	92 (47)	69 (32)	79 (37)	66 (31)	31 (13)	36 (16)	27 (15)	26 (19)
5	Scuffing wear particles – load 1000 N	0	172 (70)	135 (84)	198 (64)	131 (21)	138 (73)	154 (57)	99 (49)	91 (45)	171 (61)	97 (68)	118 (47)	70 (30)	78 (32)	75 (23)	53 (34)
6	Abrasive wear particles	0	219 (49)	187 (86)	131 (71)	91 (47)	80 (26)	67 (21)	49 (35)	36 (9)	33 (9)	34 (19)	30 (8)	22 (11)	20 (12)	23 (12)	16 (11)
7	Fatigue wear particles – load 50 N	0	144 (89)	160 (100)	108 (88)	148 (66)	126 (76)	78 (35)	81 (26)	66 (34)	77 (39)	46 (10)	64 (33)	55 (23)	44 (23)	42 (18)	49 (13)
8	Fatigue wear particles – load 100 N	0	206 (67)	203 (75)	90 (57)	111 (71)	91 (34)	99 (50)	110 (63)	112 (45)	85 (35)	99 (64)	77 (52)	79 (51)	53 (18)	52 (30)	41 (32)

6. Fractal dimension

On Figures 5 and 6, the fractal analysis examples of wear particles contour by chord method were presented. In Table 3 and on Fig. 7, the average values of the fractal dimensions for the groups of particles obtained in different processes of wear are indicated. The number of the investigated particles in each group of particles was 10. The fractal analysis showed that there are differences in the degree of complexity of wear particle contour. As can be seen from Table 3 and Fig. 7, that a wear particle with fatigue under a load of 100 N and adhesion under a load of 30 and 50 N have a greater the fractal dimension (1.16, 1.14 and 1.14) in comparison with other wear particles with scuffing under a load of 500

N, adhesion under a load 10 N and abrasion (fractal dimension = 1.09, 1.10 and 1.10). The obtained values differ depending on the size of load in the given tribological test. The increase in load causes the rise of the particles' fractal dimension. The fractal dimension of scuffing wear particles under a load of 500 N is 1.09, and under load of 1000 N, it increases to 1.12. The greater value of the particles' fractal dimension means a greater degree of the complexity of their contour. Hence, the information concerning the wear mechanism and the intensity of friction couple elements can be obtained on the basis of the fractal dimension. It is possible to improve the efficiency of the described approach by taking into consideration fractal features of particles. However, this requires the use of better solutions in research methods, including equipment and software.

a) b)

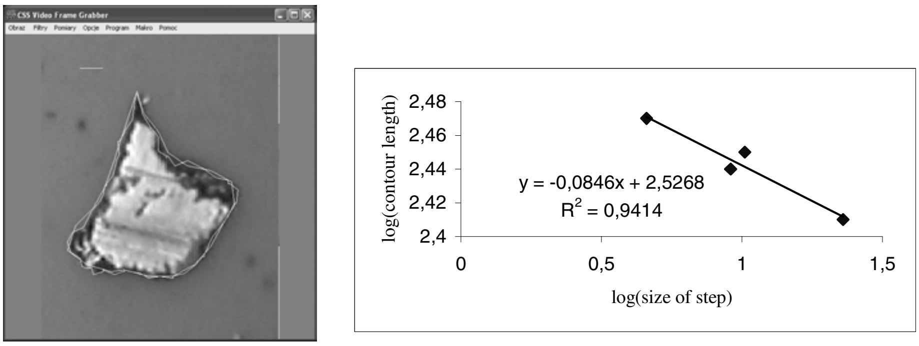

Fig. 5. The determination of the fractal dimension of the scuffing wear particles under a contact load of 500 N. The particle with marked break line (a) and regression line for relation log[*L*(*x*)] and log*x* (b)
Rys. 5. Wyznaczenie wymiaru fraktalnego cząstki zużycia scuffingowego przy obciążeniu 500 N. Cząstka z naniesioną linią łamaną (a) i linia regresji dla zależności log[*L*(*x*)] od log*x* (b)

a) b)

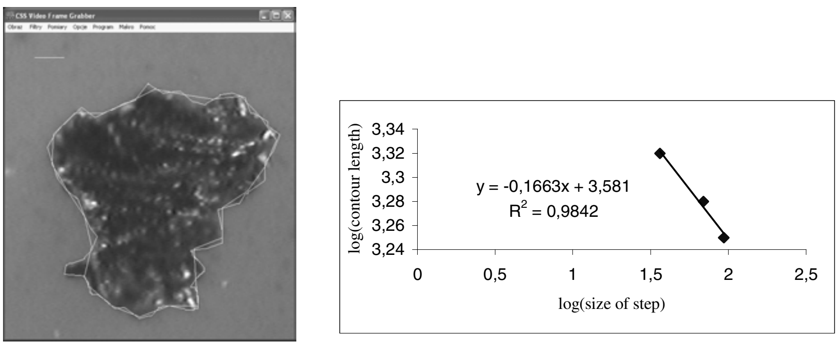

Fig. 6. The determination of the fractal dimension of the scuffing wear particles under a contact load of 1000 N. The particle with marked break line (a) and regression line for relation log[*L*(*x*)] and log*x* (b)
Rys. 6. Wyznaczenie wymiaru fraktalnego cząstki zużycia scuffingowego przy obciążeniu 1000 N. Cząstka z naniesioną linią łamaną (a) i linia regresji dla zależności log[*L*(*x*)] od log*x* (b)

Table 3. Average values of the fractal dimension for investigated types of particles
Tabela 3. Zestawienie wartości średnich wymiarów fraktalnych badanych rodzajów cząstek zużycia

No.	Wear particle type	Fractal dimension	Standard deviation
1	Adhesive wear particles – load 10 N	1.10	0.05
2	Adhesive wear particles – load 30 N	1.14	0.09
3	Adhesive wear particles – load 50 N	1.14	0.07
4	Scuffing wear particles – load 500 N	1.09	0.08
5	Scuffing wear particles – load 1000 N	1.12	0.05
6	Abrasive wear particles	1.10	0.07
7	Fatigue wear particles – load 50 N	1.13	0.07
8	Fatigue wear particles – load 100 N	1.16	0.06

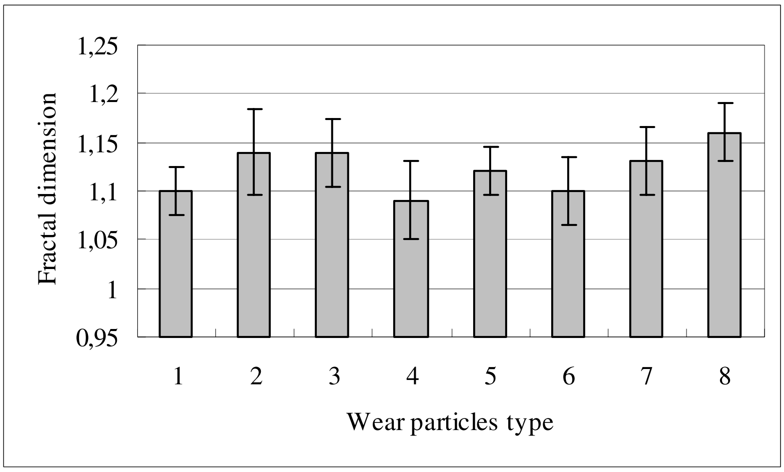

Fig. 7. The graph of the average values of the fractal dimension for the investigated types of the wear particles: adhesion under load of 10 N (1), 30 N (2), 50 N (3), scuffing under load of 500 N (4), 1000 N (5), abrasion (6) and fatigue under load of 50 N (7) and 100 N (8)
Rys. 7. Wykres wartości średnich wymiarów fraktalnych cząstek zużycia adhezyjnego przy obciążeniu styku 10 N (1), 30 N (2), 50 N (3), scuffingowego przy obciążeniu styku 500 N (4), 1000 N (5), ściernego (6) i zmęczeniowego przy obciążeniu styku 50 N (7) i 100 N (8)

7. Conclusions

The conducted research indicates that the application of the computer image analysis of wear particles in the exploitation diagnostics field of machines and technical devices enables the estimation of the current technical state of a tribological system and the prognosis of its further changes. Taking into account the development capabilities of the method, it was found that it can become an important tool for estimation of the state of friction couple in real conditions. The determination of morphological parameters opens the possibilities of the creation of databases and full documentation of the course of the wear process.

The significant practical significance of this research is connected with the application of the computer image analysis system equipped with a commonly available and applied optical microscope. The colour images of wear particles obtained with the microscope can be a carrier of information that is important from the point of view of technical diagnostics about investigated material associations. The information obtained in this way, in connection with the analysis of the construction of friction couple, and the conditions of its work, provide the possibility of the determination of the kind and state of the material of the particles and the place, reasons, and manner of their formation. By applying unified equipment and software, it will be possible to retain the comparability of research results obtained in different laboratories.

The further research for the purposes of the verification of the developed procedures, through research of wear processes running in real tribological systems, will allow the utilisation these procedures in developing a diagnosis system. In this operation, different artificial intelligence methods can be used enabling fast and unequivocal wear particle identification and the wear mechanism. The achievements in the field of electronics and informatics give the opportunity for more detailed particle research, exact analysing of the results and, on this basis of providing users information and recommendations connected with further exploitation, provide a manner for making repairs.

The results of the conducted research indicate the possibility of the application of the computer image analysis of wear particles at the stage of newly developed tribological systems as well as the time of their exploitation. It should be useful, especially in case of the large technical objects, being a single solution or by producing a short series where emergency states present a significant danger to safety and may bring serious economic losses.

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Zastosowanie komputerowej analizy obrazu w badaniach cząstek zużycia

S t r e s z c z e n i e

W pracy zbadano możliwości zastosowania komputerowej analizy obrazu do charakteryzowania tekstury, barwy i konturu cząstek zużycia. Oceny tekstury i barwy i cząstek zużycia dokonano na podstawie analizy zmian jasności i poszczególnych składowych wybranych modeli barw: RGB, HSB i CIE L*a*b*. W opisie statystycznym rozkładów zastosowano wiele parametrów, takich jak: wartość średnia, odchylenie standardowe, mediana, skośność, kurtoza. Przeprowadzono również ocenę tekstury powierzchni i konturu cząstek zużycia metodą analizy Fouriera i fraktalną. Za pomocą jednowymiarowej, szybkiej transformaty Fouriera (FFT) określono parametry liczbowe widma amplitudowego dla punktów wybranego odcinka naniesionego na obraz cząstki. W oparciu o odpowiednio przygotowane dane uzyskane z obrazów wyznaczono wymiar fraktalny konturu badanych cząstek z wykorzystaniem metody cięciw. Oceniono przydatność wyznaczonych parametrów przy ustalaniu przynależności cząstek zużycia do odpowiedniego typu. Na podstawie analizy uzyskanych wyników badań poszczególnych grup cząstek zużycia wyznaczono zależności pomiędzy cechami morfologicznymi cząstek zużycia a mechanizmami występującego zużywania węzłów tarcia.