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ANALYSIS OF IMPACT OF CHOSEN PARAMETERS ON THE WEAR OF CAMSHAFT

ANALIZA WPŁYWY WYBRANYCH PARAMETRÓW NA ZUŻYCIE WAŁKA ROZRZĄDU

The paper provides an analysis of the reasons for excessive wear of the camshafts system components based on models developed to describe the impact of selected material, technological and operational factors. The subject of the research was wear of camshaft cams studied in accordance with results of operation tests. Based on the said tests, the dependence of wear intensity of cams from their angular position was established. The respective calculation results enabled the function of cam fallibility to be determined.

Keywords: metallographic structure, wearing, friction

W artykule przedstawiono analizę przyczyn nadmiernego zużycia elementów układu rozrządu w oparciu o modele opracowane w celu opisania wpływu wybranego materiału, czynników technologicznych i operacyjnych. Przedmiotem badań było zużycie krzywek wałka rozrządu badanych zgodnie z wynikami badań eksploatacyjnych. Na podstawie tych prób ustalono zależność intensywności zużywania krzywki od ich położenia kątowego. Wyniki obliczeń pozwoliły wyznaczyć funkcję zużycia krzywki.

1. Introduction

A particularly responsible function in this system is performed by a tribological couple of a cam and a cam follower. Components of this couple are usually subject to wear of small intensity and their service life is sufficiently long [1]. However, it can happen that accelerated wear of cams and cam followers should occur during operation. Excessive wear of camshaft cams is a defect occurring in engines of various types of cars. In such cases, those components may require replacement as soon as after merely several hundred kilometers of a car's mileage. It is particularly difficult to establish the reasons for this phenomenon. Material properties are very important for camshaft cams structure. There are many publications on novel technologies for clean materials production which can be use for production of these kind elements [2-8].

Durability of the cam/follower frictional couple components may be conditional to their wear. It is defined as a process of gradual deterioration understood as the components losing their operational properties. Material properties are very significant in such kind of processes, for example surface tension [9] and quality of the process [10-14]. It is caused by input functions as well as physical and chemical factors affecting the components throughout their entire service life [15-17]. It is important to consider the novel repair technology in machine construction, especially welding methods [18-25]. The friction and wear phenomena become important issues in diagnostics and monitoring systems for Structural Health Monitoring. There are many research on vibroacoustics methods application into machine's monitoring systems [26-39]. The notion of a wear process is also related to wear as such, being an outcome of the said process expressed in the appropriate units of measure, e.g. length (linear wear), volume (volumetric wear) or mass (mass wear). The results of cam wear tests were used to determine the dependence of wear intensity from the cam's angle of rotation. The examples of friction on components of a cam/follower system have been depicted in Figure 1.

The paper presents results of two investigations on friction and wear phenomena occurring in cam/follower system.

2. Cam wear model

In the course of the laboratory studies of abrasive wear, linear wear intensity of specimens made of nodular cast iron was determined for different operating conditions and material hardness values. The results obtained enable establishing the dependence between wear intensity and the factors altered while testing. One of the solutions to determine these dependences recommended in literature is to use a wear model developed through dimensional analysis [40]. According to

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these recommendations, the following mathematical form of linear wear intensity was assumed:

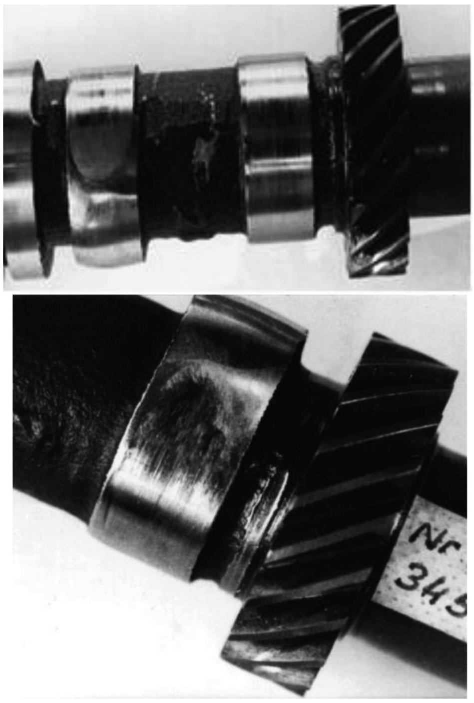

Fig. 1. Worn-out components of a cam/follower system, timing gear cam: right – on car mileage of 124 km, right – on car mileage of 154 km

$$\frac{Z}{l} = a_0 \left(\frac{p_0}{\mathrm{H}_1}\right)^{a_1} \left(\frac{\mathrm{H}_2}{\mathrm{H}_1}\right)^{a_2} \mu^{a_3}$$

where:

Z – linear wear being a liner decrement of the specimen (i.e. cam) dimension [m],

p0 – maximum Hertz pressure at the contact surface [Pa],

H1, H2 – hardness of frictional couple components (the examined and the cooperating one accordingly) [HB],

l – friction distance [m],

μ – friction coefficient,

a_0, a_1, a_2, a_3 – coefficients established by regression of the laboratory wear test results

The above function was transformed into a linear function by finding logarithms for both sides of the equation (1). It enabled using the linear regression to determine coefficients ai. The quality of the regression performed was determined using a square of the R2 correlation coefficient. The R2 value obtained came to 0.8 which implied good correlation of results of the model calculations and the laboratory tests.

Sample calculation results obtained by application of the cam wear model have been provided in Figures 2. The wear intensity calculated based on the model is then expressed in mm of linear wear for mm of friction distance, and hence relatively small values are assumed.

The dependences obtained by application of the wear model imply that the factors the model takes into consideration exert impact on the wear of both specimens and cams in operation. The largest impact on wear intensity is exerted by the friction coefficient. Therefore, it is probable that the reason for excessive wear of camshaft cams is poor lubrication causing the said coefficient to increase. Wear intensity also depends on pressure force (Fig. 2). Hence increased pressures between a cam and a cam follower due to edge-type cooperation between these components may also accelerate their wear. Consequently, the calculations based on the wear model enable assessment of the cam wear and the impact exerted by the individual factors on the possibility of its excessive wear. However, a prerequisite for those calculations to be conducted is knowing the cam and the cam follower operating conditions. For that purpose, a finite element based model of a cam/follower system was developed and subsequently used to establish the pressures occurring between these components.

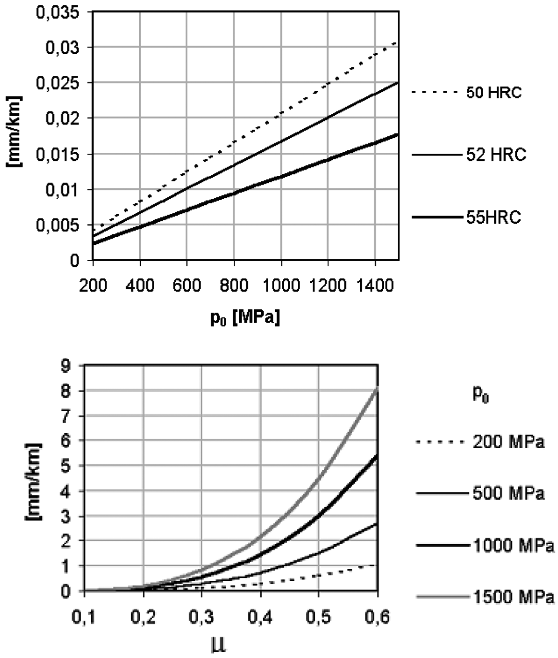

Fig. 2. Dependence between a cam's linear wear intensity and pressure force as well as its hardness on friction in presence of oil (μ = 0,1) and dependence of linear wear intensity of a cam of the hardness of 55 HRC on friction coefficient and pressure assuming the cam follower hardness of 59 HRC

3. FEM analysis – cam wear

The structural FEM models developed for a cam/follower system have been illustrated in Figure 3. The left chart shows a simplified model. The fact that a simplified model was assumed for the sake of calculations resulted from the fact that the detailed model was too large and the results obtained in the contact zone inaccurate compared to the results established for the Hertz model. In order to obtain accurate results for the contact zone one should first appropriately compact the elements of the contract zone between the cam and the cam follower. The grid of finite elements was generated using the measurement data describing a lift of a new reference cam. The cam support used enables simulation of its slight rotation. The cam follower is pressed by the pressure generated by a force depending on the cam position, and it can move vertically. The said model was noted in a parametrical form using macro commands of the COSMOS/M system, and hence it allowed for analysing contact tasks in various cam positions and changing the selected analytical parameters (e.g. dimensions, material parameters etc.). Sample maps of stresses occurring in the cam and cam follower contact zone have been provided in Figure 3.

The values of normal and tangential stresses obtained for the contact zone match the values established based on the Hertz equations well.

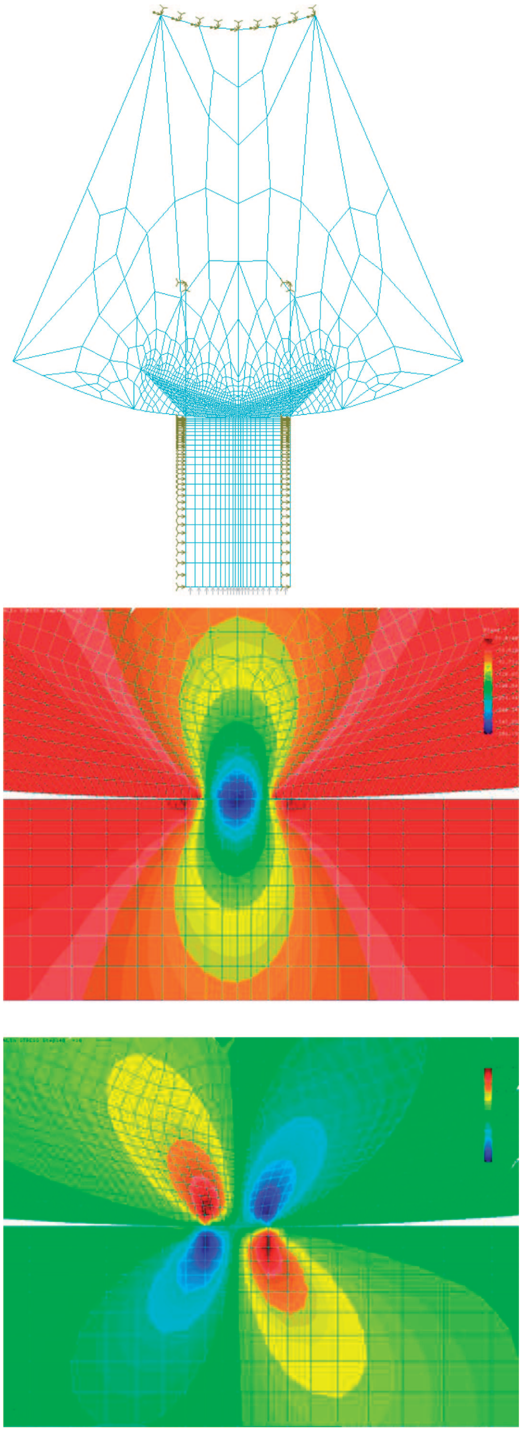

Fig. 3. The cam and follower simplified model and maps of stresses in the cam and cam follower contact zone normal and tangential

4. Wear tests for camshaft cams

The tests concerning wear of camshaft cams covered measurements of linear wear of cams of 40 camshafts dismounted from vehicle with engine with small capacity. These camshafts displayed symptoms of excessive geometric wear of certain cams. Mileages L [km] of the cars running with the camshafts subject to testing varied from 1,250 to 48,500 [km]. The relevant measurements were conducted by means of a dial gauge of the accuracy of 0.01 [mm] in a system illustrated in Fig. 2. Angle α was being altered within the range from -90 to 90° at every 5° so that the maximum cam lift could occur on the angle of ca. 0°. The lift values measured enabled calculation of each cam's wear. The linear wear was determined for individual values of angles α according to the following formula theoretical lift of a new cam minus measured lift of a worn-out cam

Since the wear in question was calculated based on measurements of cam lift against the dedendum circle (also exposed to wear), hence it was described as lift wear. The dependence between lift wear and angle has been depicted in Fig. 4 (a,b). The lift values measured enabled calculation of each cam's wear. The linear wear was determined for individual values of angles α according to the following formula:

$$Z = h_t - -h[mm],$$

where: Z – linear wear of lift, ht – theoretical lift of a new cam, h – measured lift of a worn-out cam.

In order to describe the process of excessive wear of cams, also the dependence between lift wear and car's mileage was applied. Such a dependence for angle $\alpha = 0°$ has been depicted in in Fig. 4 (c,d).

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5. Statistical analysis of the research

In order to minimise such an inconvenience, the linear lift wear intensity was analysed, being a relationship between linear wear Z of cam lift expressed in millimetres and mileage L expressed in kilometres:

$$I_{EW} = \frac{Z}{L} \left[\frac{mm}{km}\right]$$

Intensity IEW was called "operational", since a reference was made between the wear and the car's mileage (and not friction distance, as it usually happens while analysing various frictional couples). The operational cam lift wear intensity illustrated in Fig. 5 (a,b) usually displays two maxima: the smaller one for $\alpha = -40°$ and the larger one for $\alpha = 30°$. In order to establish their values, a mean and a median (value occurring in the middle of a set after it has been arranged) were determined for the wear intensity. Fig. 5 (c,d) confirms the foregoing statement concerning two maxima of wear intensity.

The decisive factor for a cam's durability is the highest intensity of its wear.

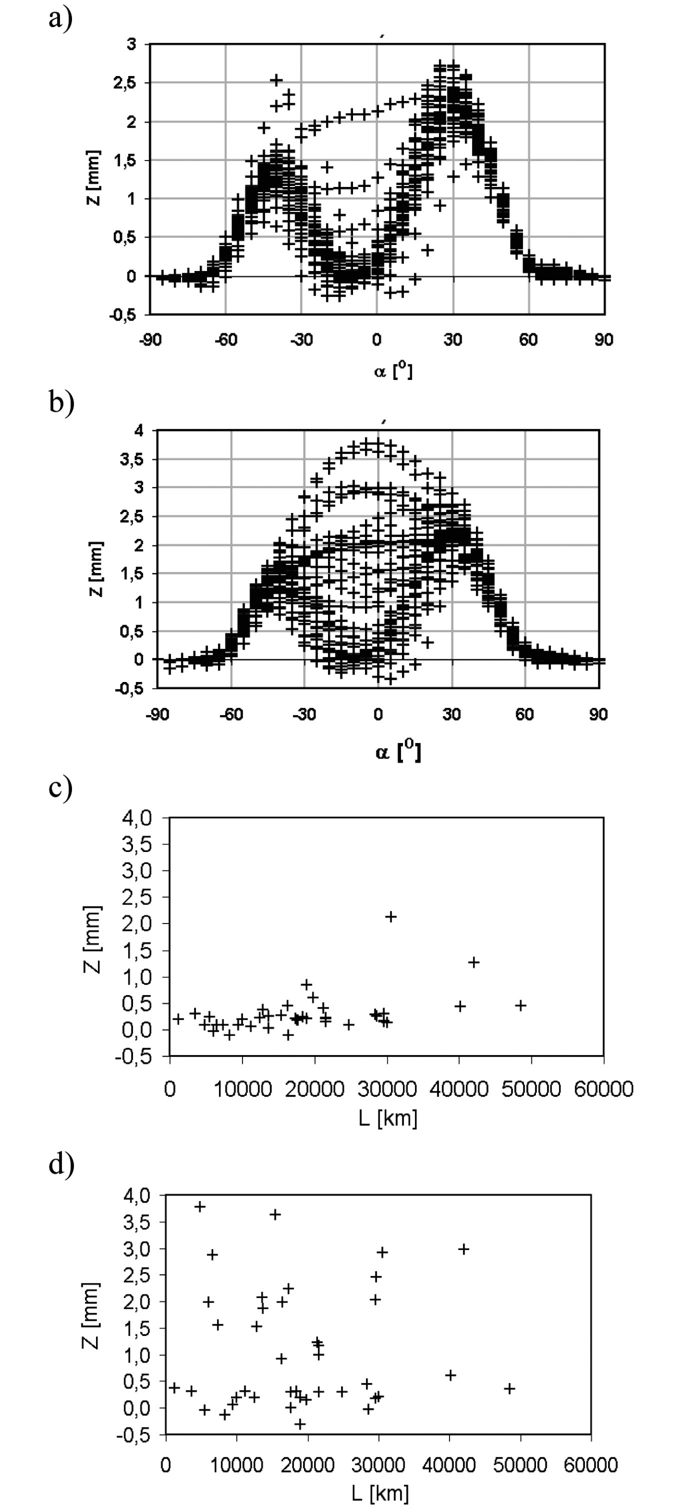


Fig. 4. Dependence of linear lift wear of the cams tested from angle α for the following cam types: a) 1 intake, b) 1 exhaust, and dependence of linear lift wear for angle α = 0° from mileage for the following cam types: c) 1 intake d) 1 exhaust

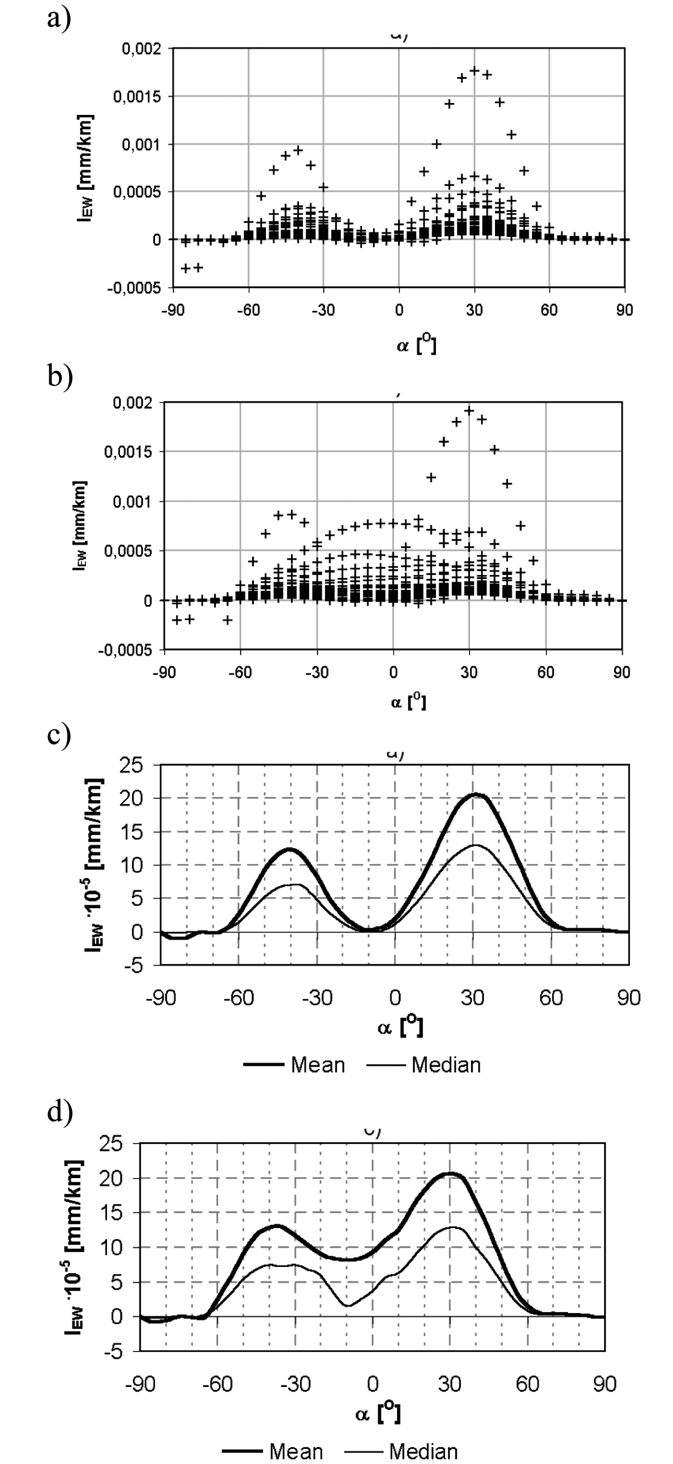


Fig. 5. Operational cam lift wear intensity in the function of angle α: a) intake cam 1, c) exhaust cam 1, Mean and median for relative operational wear intensity in the function of angle α: a) intake cam 1, c) exhaust cam 1

Having conducted the foregoing tests and calculations, one may reach the following conclusions: Wear intensity of the camshaft cams examined is a function of the cam's angle of rotation. This dependence is characterised by occurrence of two maxima for the angles of ca. -40° and 30°. The reasons for such a state of matters can only be assessed after pressure calculations are conducted taking the relevant dynamic forces into consideration.

6. Metallographic tests

Worn-out cams and cam followers were subject to metallographic tests using a light microscope and a scanning one in order to establish their material structures and wear mechanisms. The scanning microscope was used to examine the areas near the wear surface. The observations conducted proved that nearly in all cases, in the cams being examined, both excessively and properly worn-out, there were irregularities due to ridging and scratching accompanied by micro-cracking. Sample results of the metallographic tests of cams have been provided in figures below. An analysis conducted on the metallographic test results obtained enabled excluding certain possible reasons for the excessive wear of cams and cam followers, and proved the necessity of further laboratory and simulation tests.

a)

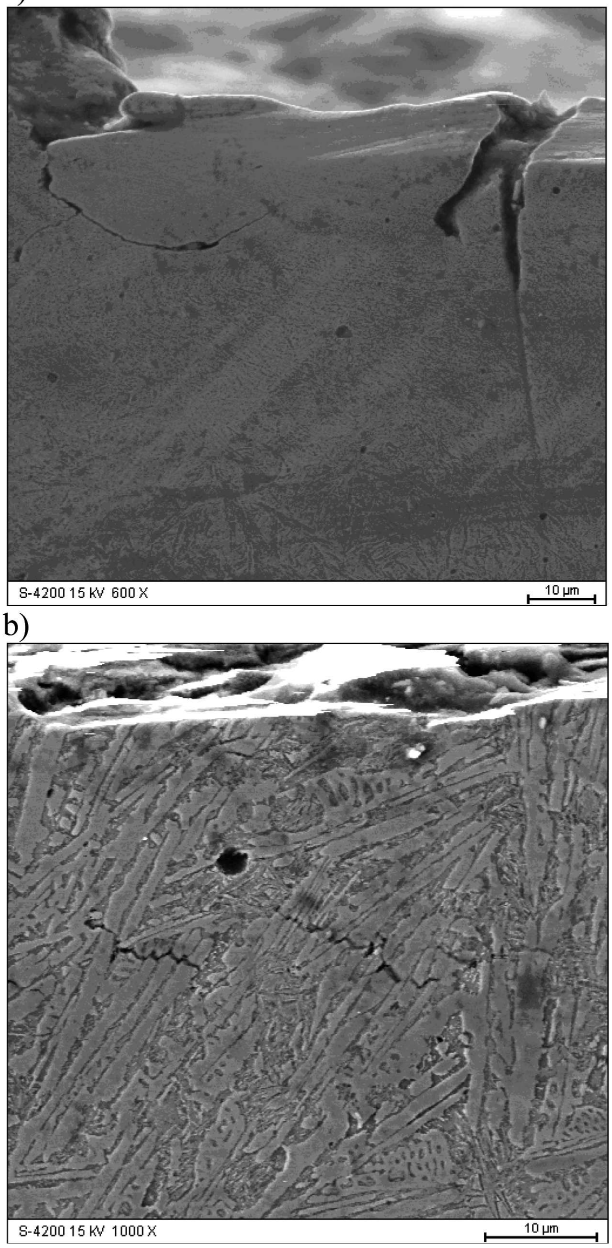


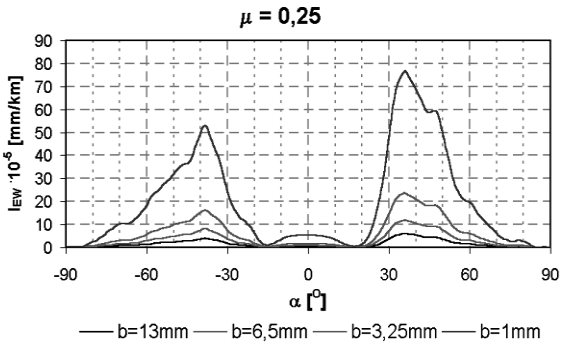
Fig. 6. Visible micro-cracks near the wear surface (damaged cam, nital etching, magnification of 600x) – a, near-surface micro-cracks in the eutectic structure (damaged cam, nital etching, magnification of 1000x) – b

Based on an analysis of the results of wear intensity calculations obtained as a result of the geometry measurements for excessively worn-out camshaft cams, one could conclude that the most probable reasons for excessive wear of cams and cam followers included inferior lubrication quality resulting from too low oil viscosity, too high oil temperature or low pressure in the lubrication system which may be accompanied by edge-type cam and follower cooperation.

7. Research on impact of the cam and follower cooperation and of lubrication on the cam wear

The wear model and the FEM model which allow for determination of the stresses occurring in a cam/follower system enable analysis of the reasons for excessive wear of cams by establishing the impact exerted by the most significant material, technological and operational factors on the wear and durability of cams. The study in question entailed the dependence of wear and durability on edge-type cooperation between a cam and a cam follower (modelled through a decreased contact width) and lubrication quality (determined by application of the friction coefficient). In order to determine whether the edge-type cooperation between the cam and the cam follower may cause excessive wear of cams, using the FEM model of the cam/follower system, the Hertz pressures were established on different contact widths b. Next, by inserting those stresses into equation (1), the linear wear intensity in the function of cam's angle α was established. The linear wear intensity calculated based on the wear model determines the wear (in mm) per 1 km of friction distance. Whereas in the tests of worn-out camshaft cams, a different wear intensity was established, namely the operational one expressed as a relationship between cams' linear wear and car mileage. In order to be able to compare the results of wear model calculations with the results of cam tests, the friction distance was converted into car mileage. The calculation results obtained with regard to relative operational wear intensity of a cam conditional to angle α on different widths b of the contact between the cam and the cam follower have been depicted in Figure 7a. The wear in question is the largest on angle α = 36.5° regardless of the friction coefficient value or the contact width. Therefore it is decisive for durability of cams. A comparison of the model calculation results and the actual state of matters has been provided in Figure 7b which depicts a median of the relative operational wear intensity of cams obtained based on measurements of worn-out cams (marked as "Exp") collated with the curves obtained in the calculations illustrated in Figure 7a. Having analysed the curves depicted in Figure 7b, one may claim that the curves are qualitatively similar. All graphs have two maxima. Angles α, on which the maxima occur, are similar. The shape differences for the curves being analysed result from the impact of wear, changing the cam profile, exerted on the pressures and the contact dimensions being decisive for further wear of cams. As a result of what is referred to as "feedback", the operation curve becomes a little smoother, and the wear intensity maxima are slightly shifted towards smaller angles. For the first maximum, on angle α = -40°, the shift does not exceed 5° being a value exactly corresponding to the operational measurements. For the maximum decisive for the cam durability, the difference comes to ca. 6.5°.

a)



b)

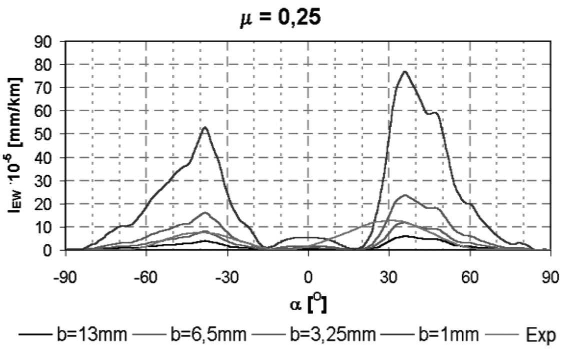


Fig. 7. Dependence of cams' operational wear intensity IEW on angle α on different values of width b of the cam and cam follower contact (cam hardness of 55 HRC and cam follower hardness of 59 HRC) for the friction coefficient equalling 0.25 (a) and (b) operational dependence calculated based on the model for the friction coefficient of 0.25 and based on the operation ("Exp")

8. Conclusions

Wear intensity and durability of cams are strongly dependent on the value of friction coefficient (lubrication). An increase of the friction coefficient from lubricated contact to dry friction reduces the cam durability by two orders of magnitude. Also the contact width (edge-type cooperation between a cam and a cam follower) exerts a significant impact on durability of cams. Wear intensity of the camshaft cams examined is a function of the cam's angle of rotation. This dependence is characterised by occurrence of two maxima for the angles of ca. -40° and 30°. The reasons for such a state of matters can only be assessed after pressure calculations are conducted taking the relevant dynamic forces into consideration. Furthermore, the cam durability is considerably affected by the material the cam and the cam follower are made of. Raising the cam hardness from 50 to 55 HRC increases its durability. A similar effect is observed when the cam follower hardness is reduced from 59 to 53 HRC. By comparing the model calculation results with the actual state of matters, one could draw the following conclusions pertaining to the reasons for excessive wear of cams.The main reason for excessive cam wear is inferior quality of the cam and follower frictional couple lubrication which manifests itself in an increase of the coefficient of friction between these components. At the same time, one can observe a considerable impact of the contact width as well as the hardness of cams and cam followers on their wear. In order to counteract the phenomenon of accelerated wear of cams, one should consider increasing the required hardness of their working surfaces.

REFERENCES

[1] R. Burdzik, P. Folęga, B. Łazarz, Z. Stanik, J. Warczek, Analysis of the impact of surface layer parameters on wear intensity of frictional couples, Archives of Metallurgy and Materials **57** (4), 987-993 (2012).

[2] L. Blacha, Bleientfernung aus kupferlegierungen im prozess der vakuumraffination, Archives of Materials and Metallurgy **48** (1), 105-127 (2003).

[3] Z. Dąbrowski, P. Deuszkiewicz, Designing of high-speed machine shafts of carbon composites with highly nonlinear characteristics, Key Engineering Materials **490**, 76-82 (2011).

[4] A. Dąbrowska, P. Deuszkiewicz, A. Huczko, Nanokompozyty sic/żywica epoksydowa – nowy materiał konstrukcyjny w przemyśle jachtowym, Przegląd Mechaniczny **5**, 2013.

[5] Z. Dąbrowski, P. Deuszkiewicz, Nonlinear dynamic model of a carbon-epoxy composite structure, 20th International Congress On Sound & Vibration ICSV 20, Bangkok (2013).

[6] A. Fornalczyk, M. Saternus, Platinum recovery from used auto catalytic converters in electrorefining process. Metalurgija **52**(2), 219-222 (2012).

[7] J. Mańkowski, J. Osiński, P. Żach, Tension field in thin walled aeronautical girders, Mechanics And Mechanical Engineering **14** (2), 291-308 (2010).

[8] W. Sitek, A mathematical model of the hardness of high-speed steels, Transactions Of Famena **34** (3), 39-46 (2010).

[9] G. Siwiec, B. Oleksiak, A. Smalcerz, J. Wieczorek, Surface tension of Cu-Ag alloys, Archives of Materials and Metallurgy **58** (1), 193-195 (2013).

[10] L. Blacha, R. Burdzik, A. Smalcerz, T. Matuła, Effects of pressure on the kinetics of manganese evaporation from the ot4 alloy, Archives Of Metallurgy and Materials **58** (1), 197-201 (2013).

[11] B. Oleksiak, A. Blacha-Grzechnik, G. Siwiec: Application of the flotation process in the silver recovery from the wastes generated during the silvery semi-products manufacturing. Metalurgija **51** (3), 298-300 (2012)

[12] B. Oleksiak, L. Blacha, Kinetics of lead removal from the cu-pb-fe alloy by barbotage with inert gases, Metalurgija **50** (2), 89-92 (2011).

[13] A. Smalcerz, R. Przyłucki, Electromagnetic field analysis of inductor-robot-work-piece system, Metalurgija **52** (2), 223-226 (2013).

[14] A. Karbownik, K. Dohn, K. Sienkiewicz-Małyjurek, Value chain analysis of environmental management in urban – case study, Metaropolitan association of Upper Silesia, Polish Journal of Environmental Studies **21**, 911-921 (2012).

[15] A. Kaźmierczak-Bałata, J. Bodzenta, D. Trefon-Radziejewska, Determination of thermal-diffusivity dependence on temperature of transparent samples by thermal wave method, International Journal of Thermophysics **31** (1), 180-186 (2010).

[16] M. Dzida, S. Jężak, J. Sumara, M. Żarska, P. Góralski, High pressure physicochemical properties of

biodiesel components used for spray characteristics in diesel injection systems. Fuel **111**, 165-171 (2013).

[17] M. D z i d a, P. P r u s a k i e w i c z, The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel. Fuel **87**, 1941-1948 (2008).

[18] A. L i s i e c k i, Welding of titanium alloy by Disk laser. Proceedings of SPIE, Laser Technology, Applications of Lasers **87030** (2013).

[19] T. W ę g r z y n, D. H a d r y ś, M. M i r o s, Optimization of Operational Properties of Steel Welded Structures, Maintenance and Reliability **3** (2010).

[20] T. W ę g r z y n, J. M i r o s ł a w s k i, A. S i l v a, D. P i n t o, M. M i r o s, Oxide inclusions in steel welds of car body, Materials Science Forum 636-637 (2010).

[21] A. L i s i e c k i, Diode laser welding of high yield steel. Proceedings of SPIE, Laser Technology, Applications of Lasers **8703**, 22 (2012).

[22] T. W ę g r z y n, Mathematical Equations of the Influence of Molybdenum and Nitrogen in Welds. Conference of International Society of Offshore and Polar Engineers ISOPE′ 2002, Kita Kyushu, Japan 2002, Copyright by International Society of Offshore and Polar Engineers, vol. IV, ISBN 1-880653-58-3, Cupertino – California – USA 2002.

[23] T. W ę g r z y n, The Classification of Metal Weld Deposits in Terms of the Amount of Oxygen, Proceedings of the Conference of International Society of Offshore and Polar Engineers ISOPE'99, Brest, France 1999, International Society of Offshore and Polar Engineers, vol. IV, Cupertino – California, USA, 212-216 (1999).

[24] T. W ę g r z y n, J. P i w n i k, A. S i l v a, M. P l a t a, D. H a d r y ś, Micro-jet technology in welding, The 23-Rd (2013) International Ocean (Offshor) And Polar Engineering Conference, proceedings of isope-2013 Anchorage, Alaska, USA, 178-180 (2013).

[25] T. W ę g r z y n, J. P i w n i k, R. W i e s z a l a, D. H a d r y ś, Control over the steel welding structure parameters by micro-jet cooling, Archives Of Metallurgy And Materials **57**(3), 679-684 (2012).

[26] R. B u r d z i k, Ł. K o n i e c z n y, T. F i g l u s, The possibility to control and adjust the suspensions of vehicles,, J. Mikulski (Ed.): Activities of Transport Telematics, TST, CCIS **395**, 378-383 (2013).

[27] R. B u r d z i k, Research on the influence of engine rotational speed to the vibration penetration into the driver via feet – multidimensional analysis, Journal of Vibroengineering **15**(4), 2114-2123 (2013).

[28] R. B u r d z i k, Identification of structure and directional distribution of vibration transferred to car-body from road roughness, submitted to Journal of Vibroengineering **16**(1), 324-333 (2014).

[29] R. B u r d z i k, Z. S t a n i k, J. W a r c z e k, Method of assessing the impact of material properties on the propagation of vibrations excited with a single force impulse, Archives of Materials and Metallurgy **57**(2), 409-416 (2012).

[30] K. R a g u l s k i s, K. K a n a p e c k a s, R. J o n u š a s, K. J u z ė n a s, Vibrations generator with a motion converter based on permanent magnet interaction, Journal of Vibroengineering **12**(1), 124-132 (2010).

[31] M. R a g u l s k i s, V. K r a v č e n k i e n e, K. P i l k a u s k a s, R. M a s k e l i u n a s, L. Z u b a v i č i u s, P. P a š k e v i č i u s, Calculation of stresses in the coating of a vibrating beam, Journal of Vibroengineering **11**(4), 707-711 (2009).

[32] R. M i c h a l s k i, S. W i e r z b i c k i, An analysis of degradation of vehicles in operation. Maintenance and Reliability **1**(37), 30-32 (2008).

[33] B. P o j a w a, Tests of LM2500 naval gas turbine with the objective of determining its operating characteristics, Diagnostyka – Diagnostics and Structural Health Monitoring **4**(60), 65-70 (2011).

[34] A. W i l k, H. M a d e j, T. F i g l u s, Analysis of the possibility to reduce vibroactivity of the gearbox housing. Eksploatacja i Niezawodność – Maintenance and Reliability 2(50), 42-49 (2011).

[35] R. Z i m r o z, J. U r b a n e k, T. B a r s z c z, W. B a r t e l m u s, F. M i l i o z, N. M a r t i n, Measurement of instantaneous shaft speed by advanced vibtation signal processing – application to wind turbine gearbox. Metrology and Measurement Systems **18**(4), 701-711 (2011).

[36] D. D ą b r o w s k i, W. B a t k o, W. C i o c h, Model of the Gears Based on Multibody System and Its Validation by Application of Non-Contact Methods, Acta Physica Polonica A, **123** (6), 1016-1019 (2013).

[37] A. G r z ą d z i e l a, Modelling of propeller shaft dynamics at pulse load, Polish Maritime Research **15** (4), 52-58 (2008).

[38] M. K ł a c z y ń s k i, T. W s z o ł e k, Artificial intelligence and learning systems methods in supporting long-term acoustic climate monitoring. Acta Physica Polonica A, **123** (6), 1024-1028 (2013).

[39] M. K ł a c z y ń s k i, T. W s z o ł e k, Detection and classification of selected noise sources in long-term acoustic climate monitoring. Acta Physica Polonica A, **121** (1-A), 179-182 (2012).

[40] W. Z w i e r z y c k i et al., Selected aspects of material wear in slide friction pairs, PWN, Warsaw-Poznań, (1990) (in Polish).

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