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THE EFFECT OF SURFACE ROUGHNESS AND MATERIAL HARDNESS ON THE TRIBOLOGICAL PERFORMANCE OF THE SLIDING PAIR WC-42CrMo4 UNDER STARVED LUBRICATION

WPŁYW CHROPOWATOŚCI POWIERZCHNI I TWARDOŚCI MATERIAŁU NA WŁAŚCIWOŚCI TRIBOLOGICZNE WĘZŁA ŚLIZGOWEGO WC-42CrMo4 PRZY SKĄPYM SMAROWANIU

Key words: tungsten carbide (WC), surface roughness, tribological performance.

Abstract: Ceramic materials are more and more popular in industrial applications. Machine elements made of ceramic materials are characterized by long durability, especially those elements that work in hard operating conditions. In this paper, the results of tribological examinations of WC-42CrMo4 sliding pair are presented. Tribological tests were realized with the T-11 stand with the ball-on-disc sliding pair. For lubrication, the machine mineral oil L-AN 46 was used. The analysis showed that surface roughness significantly affected the tribological performance of tested sliding pairs. Steel samples were characterized with various hardnesses in the range of 22–42 HRC and this feature also effected on friction coefficient. Statistical analyses of the achieved results were made using the 3-level PS/DC 3^2 design. According to the statistical analysis, the quadratic functions describing the dependence for friction coefficient on surface roughness and material hardness were obtained. The most unfavourable surface roughness was after the grinding process, but the best was those after the lapping process which allows the smallest friction coefficient.

Słowa kluczowe: węglik wolframu (WC), chropowatość powierzchni, charakterystyki tribologiczne.

Streszczenie: Materiały ceramiczne znajdują coraz większe zastosowanie w urządzeniach przemysłowych. Elementy maszyn wykonane z materiałów ceramicznych charakteryzują się znaczną trwałością, szczególnie te elementy, które pracują w trudnych warunkach. W artykule przedstawiono wyniki badań tribologicznych węzła ślizgowego w skojarzeniu materiałowym WC-42CrMo4. Badania tribologiczne zrealizowano w wykorzystaniem testera T-11 z węzłem ślizgowym typu kula–tarcza. Do smarowania węzła tarcia zastosowano olej maszynowy L-AN 46. W wyniku analizy wykazano, że chropowatość powierzchni w istotny sposób wpływa na charakterystyki tribologiczne badanych węzłów ślizgowych. Stalowe próbki charakteryzowały się zróżnicowaną twardością w zakresie 22–42 HRC, co również wpływało na opory ruchu. Plan statyczny zdeterminowany kompletny PS/DC 3^2 posłużył do analizy statystycznej wyników badań. Otrzymano funkcje kwadratowe obrazujące zależności współczynnika tarcia od chropowatości powierzchni i twardości materiału. Najmniej korzystne wyniki uzyskano przy zastosowaniu powierzchni szlifowanych, natomiast najmniejsze wartości współczynnika tarcia otrzymano przy badaniu powierzchni docieranych.

INTRODUCTION

The sliding pairs that consist of mono-metals such as steel-steel or steel-cast iron are characterized by a high coefficient of friction and high wear **[L. 1–3]**. These values can be reduced by using different types of metals in the tribological pair, and they are usually designed in a particular way. Due to application of the different type of material, the adhesive wear may be limited or eliminated. In hard operating conditions when the load is large, temperature is high, or the co-acting elements work in a corrosive environment, low-friction

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coatings could be also the option to reduce friction and wear. Tuszyński et al. **[L. 4]** applied a low-friction WC/C coating and obtained a reduction in the wear of gears wheel. Madej and Ozimina **[L. 5]** tested sliding elements with DLC (diamond-like carbon) coatings of types a-C:H and a-C:H:W on the CoCrMo alloy. DLC coatings are characterized by high elastic modulus, resistance to fracture, a low coefficient of thermal expansion, chemical stability, and a sliding pairs with such coating operate with a low friction coefficient. Authors of **[L. 5]** obtained a 7-times lower coefficient of friction of a sliding pair with DLC coating (a-C:H) in comparison to a series with elements without a coating (CoCrMo alloy) under technically dry friction. Beside the specific material properties, the a-C:H coating was characterized with a lower surface roughness (Ra = 3.7 nm) than the other series, i.e. a base CoCrMo (Ra = 12 nm) and with coating a-C:H:W (Ra = 44.8 nm), which could also influence the wear **[L. 6]**. The wear intensity was 7-times lower than the base series in technically dry friction and approximately 25% lower than base series under lubrication **[L. 6]**. Application of DLC coating of type Ti/a-C:H:W on SW7M steel allowed obtaining a lower friction coefficient of 60% and a reduction of wear of 90%, comparing to the sliding pair without coating: 100Cr6-SW7M **[L. 7]**.

Composite coatings like Ni-SiC, Ni-TiN, and Ti-Al_2O_3 sprayed on steel elements with high pressure and high velocity are also an option to improve the tribological characteristics. In technically dry friction and under starved lubrication conditions, the sliding pairs with ceramic composite coatings (Ni-SiC, Ni-TiN, and Ti-Al_2O_3) operated with a lower friction force than the pairs where the disc was coated only with Ni **[L. 8]**.

The problem with the wear of materials arises especially under high load and then the coatings could reduce the wear intensity. Kasprzycka et al. **[L. 9]** compared the wear in the wide range of the applied loads pressed against elements with coatings of CrC+CrN, CrC and a base series without coating (X210Cr12 steel). Implementation of the coating under 50 MPa of pressure gave approximately 20–25% reduction of the linear wear, but under the highest load of 400 MPa of pressure, the wear was smaller by over 4-times in comparison to the series without coating **[L. 9]**.

Zimowski et al. **[L. 10]** noticed the problem of the load carrying capacity of multilayer coatings. Implementation of ceramic coatings has many advantages, like low friction and wear of sliding pair, but the load capacity of the system ceramic coating-substrate is limited and when the load capacity is exceeded causing the wear to increase dramatically. Authors of **[L. 10]** compared the friction coefficient values of sliding pairs with multilayers coatings and found that the elements with the greatest number of layers (TiN/CrN)-32 were superior to other series: (TiN/CrN)-2 and (TiN/CrN)-8. Series with 32 layers of TiN and CrN showed the greatest load carrying capacity and wear resistance. Zimowski **[L. 11]** analysed how the hardness and elastic modulus influenced the wear of the composite coatings. The great hardness and stiffness of the coating-substrate system led to fracture propagation and the crumbled hard particles intensified the wear of the sliding element with multilayer coating CrN(Cr/CrN)x5.

The problem of the failure mechanisms of coating-substrate under the load is also described in **[L. 12, 13]**. Authors analysed the fracture and wear resistance of multilayers coatings and found that, by introducing a metallic layer of Ti, it is possible that Ti layers could slide on other layers of TiN or a-C:H and compensate the pressure from the applied load **[L. 13]**.

Ceramic materials are increasingly used for the production of machine components working in difficult operating conditions **[L. 14]**. Ceramic materials are characterized by high hardness and corrosion resistance, and, mainly because of these features, they found applications in machines, devices, and tools **[L. 15]** that works in hard operating conditions. Bulikowska and Gałda **[L. 1]** found that the implementation of the silicon carbide (SiC) ceramic instead of a steel sliding element in lubricated contact reduced the friction force significantly. According to the results, the friction force is influenced by the surface roughness and material hardness of the co-acting steel elements. The use of a ceramic element (SiC) in the friction sliding pair allowed the reduction of the coefficient of friction by 17% in comparison to the value of friction coefficient of the sliding pair with the steel-steel material combination when the hardness of the disc was 42 HRC and average roughness Ra was equal to 0.24 μm **[L. 1]**.

Surface roughness of sliding surfaces has a significant impact on the movement resistance and wear of machine parts **[L. 16]**. The use of additional surface finishing treatment allows the reduction of the coefficient of friction of SiC-42CrMo4 sliding pair by 6–12%, in addition, no visible signs of wear after friction tests were observed on tested surfaces **[L. 1]**. The material hardness of the steel element of the sliding pair showed a significant but small influence on the motion resistance under low load (5 N).

Dzierwa **[L. 3]** analysed the application of different ceramic materials in dry sliding contact and established that volume wear of a steel disc co-acted with Al_2O_3 ceramic was approximately twice-greater than that of the discs mated with ceramics SiC, WC, Si_3N_4, and ZrO_2. The wear and friction force of sliding pair type ceramic-steel in dry contact depended on the surface roughness of the steel element.

Ceramic elements have found more and more implementations. In medicine, the ceramic materials are used for the femoral head of endoprosthesis, but the manufacturing process is still difficult and complicated **[L. 17]**. Properly adjust kinematics of process and technological parameters allow one to achieve a high quality of the surface and an accurate product that substitute the real part of the human joint **[L. 18]**.

The aim of this study is to analyse the implementation of WC ceramic to sliding pairs under starved lubrication conditions. The effect of surface roughness of steel element and hardness of steel disc on the coefficient of friction is analysed.

EXPERIMENTAL PROCEDURE

Tribological tests were conducted with the tester T-11. The sliding pair consists of ball and disc. Balls of 6.35 mm in diameter were made of tungsten carbide (WC). Selected mechanical properties of WC are presented in **Table 1**. To justify the subject of the research and for comparison the results, the sliding pair with steel ball of 100Cr6 was also tested. The mean roughness of tested balls was quite similar; the Ra of steel balls was equal to 0.032 µm on average and Ra parameter of ceramic balls was approximately equal to 0.035 µm. To simulate the hard operating conditions, the tests were conducted at a low sliding speed equal to 0.08 m/s and a small portion of oil was added between elements. One drop of machine mineral oil L-AN 46 was smeared on the steel disc surface to leave a thin layer of the lubricant. Tests were realized at the ambient temperature equal approximately to 21°C. Tests were repeated three times.

Table 1. Selected mechanical properties of tungsten carbide (WC)

Tabela 1. Wybrane właściwości mechaniczne węglika wolframu (WC)

Properties	Value for WC
Hardness [HV]	1670
Young's modulus [GPa]	630
Poisson's coefficient	0.24
Resistance for cracking [MPa/m]	10

Steel discs were made of 42CrMo4 with various hardnesses in the range of 22–42 HRC. Surface roughness was prepared in three different variants. Ground discs surfaces were the base series, and the average height of surface irregularities characterized by the Ra parameter was equal to 0.24 µm. The second series was obtained after a polishing process and the roughness was reduced to 0.14 µm on average, mainly by the reduction of the peaks' heights. The third series was characterized by 0.04 µm on average of the Ra parameter. Such small surface irregularities heights were achieved by the lapping process. In **Fig. 1**, surface profiles of examined steel discs of various surface finishes are presented. Amplitude roughness and material ratio parameters were calculated with the application of TalyProfileLite v6 software according to the PN-ISO 4287 standard.

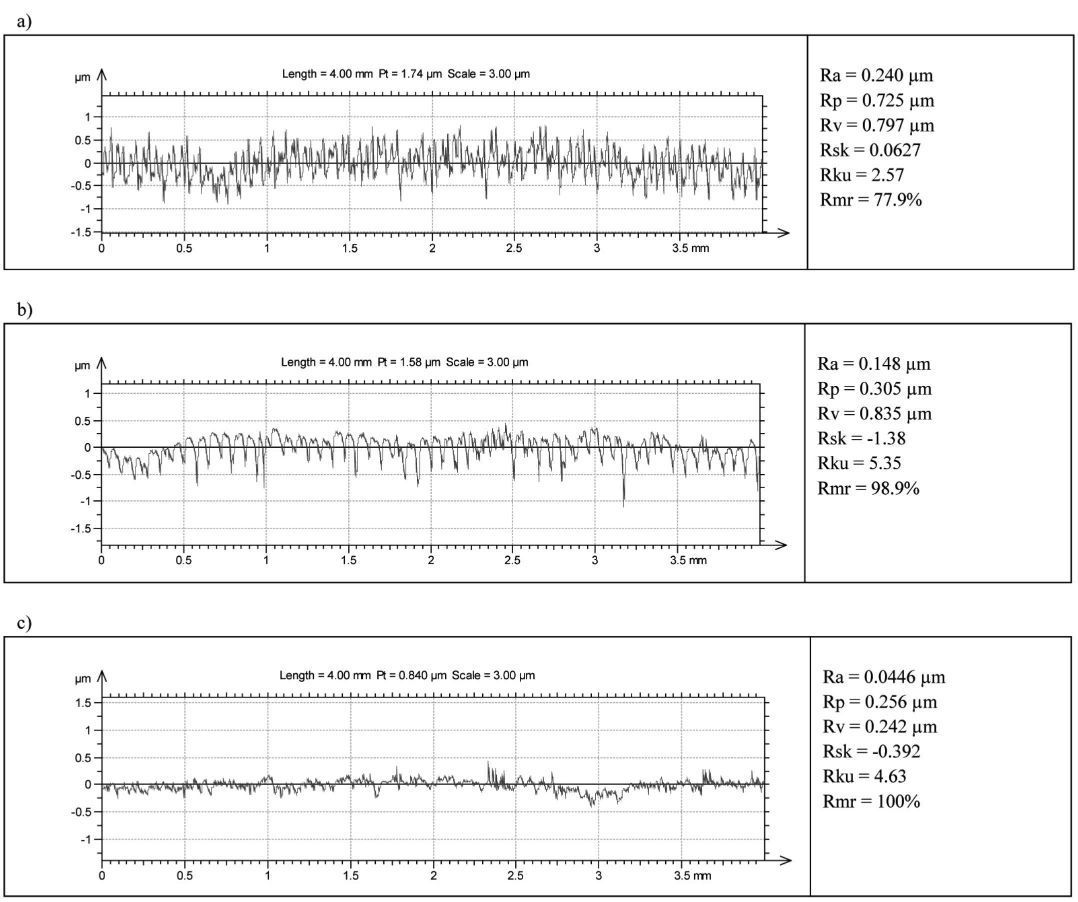


Fig. 1. Surface profiles and selected roughness parameters of steel discs: ground (a), polished (b), and after lapping (c)

Rys. 1. Profile i wybrane parametry chropowatości powierzchni stalowych dysków: szlifowane (a), polerowane (b) i docierane (c)

As a result of additional surface treatment, the significant reduction of peaks heights (Rp) was obtained of over 50% after polishing and over 60% after lapping, compared to the Rp of ground surfaces. The decrease in the valley depths was obtained only after lapping, but, in both modified series, the skewness of surface profiles Rsk became negative and material ratio Rmr increased. To analyse the influence of two factors, i.e. surface roughness and material hardness, on the friction coefficient, the PS/DC 3^2 design was used. The PS/DC 3^2 design is a universal one because allows one to obtain a quadratic polynomial but linear terms are also possible to achieve when relevant coefficients are reduced. The general polynomial function of second degree with two variables x_1 and x_2 that could be obtained according to the 3-level completed PS/DC 3^2 design is presented below:

$$y = b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 + b_1x_1 + b_2x_2 + b_0 \quad (1)$$

where b_0,..., b_{12} are the coefficients of the terms.

The material hardness (T) and surface roughness (Ra) where assumed as input parameters and the coefficient of friction was the output parameter. Values of input parameters in three levels are presented in **Table 2**.

Table 2. Values of input parameters: material hardness T and surface roughness Ra of steel discs

Tabela 2. Wartości czynników wejściowych: twardość materiału T i chropowatość powierzchni Ra stalowych tarcz

Input factors	T [HRC]	Ra [µm]
the maximum (+)	42	0.24
the central (0)	32	0.14
the minimum (–)	22	0.04
Output factor	µ	

Coded input parameters are as follows:

$$x_1 = \frac{\hat{x}_1 - \hat{x}_{10}}{\Delta\hat{x}_1} = \frac{T - 32}{10} \quad (2)$$

$$x_2 = \frac{\hat{x}_2 - \hat{x}_{20}}{\Delta\hat{x}_2} = \frac{Ra - 0.14}{0.1} \quad (3)$$

where $\Delta\hat{x}_1$, $\Delta\hat{x}_2$ are the central values and $\hat{x}_{10}$, $\hat{x}_{20}$ are the variability units.

To assess whether the experiment was realized with a sufficient reproducibility, the Cochran's statistic was applied. The coefficients of terms of the polynomial were judged with the t-Student's statistic. The adequacies of the polynomials were examined with the usage of the Fisher-Snedecor function. Tribological tests were realized for three various loads: 5 N, 10 N, and 20 N.

RESULTS AND DISCUSSION

The base series was composed of steel-steel elements, and it was tested before the main experiments according to the PS/DC 3^2 design were realized. The base series was tested at the small load of 5 N and steel disc hardness was 42 HRC after heat treatment. The roughness of the steel disc was equal approximately to 0.04 µm. There was a thin layer of machine oil L-AN 46 on disc surface. Courses of friction force values for analysed sliding pairs are presented in **Fig. 2**. Application of the ceramic element WC caused the decrease in the friction force of approximately 30% in comparison to friction force of mono-material sliding pair. Although the load was really small and the hardness was quite high of the steel disc, the difference in movement resistance was significant. That means that it is reasonable to substitute the steel element by the ceramic WC element in a sliding pair under starved lubrication.

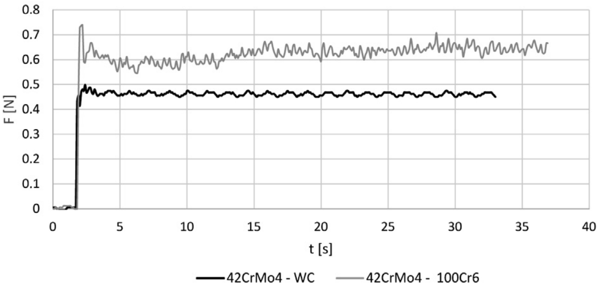


Fig. 2. Courses of friction force values for sliding pairs consist of mono-materials and with ceramic WC application

Rys. 2. Przebiegi siły tarcia par ślizgowych: jednoimiennej i z zastosowaniem elementu ceramicznego WC

As the main part of the research was the effect of material hardness of 42CrMo4 steel and also the surface roughness of the steel discs on the friction coefficient of sliding pairs with the ceramic WC element, the tests were realized at three various loads. The sliding pairs composed of WC-42CrMo4 were tested under the loads of 5 N, 10 N, and 20 N. In **Table 3**, the average values of the coefficient of friction for different operating conditions are presented.

According to average values of friction coefficient, one can say that the greatest values of µ are found for the highest roughness characterized by the Ra parameter. The friction coefficient of sliding pair WC-42CrMo4 with the ground disc surface (Ra = 0.24 µm) decreased when the hardness of steel discs increased. With the increase of the load, the coefficient also increased in most analysed cases. The greatest improvement of tribological characteristics was observed when sliding pairs consisted of the steel element with the smallest hardness of 22 HRC. The coefficient of friction after applying additional lapping process (Ra = 0.04 µm) was approximately 10% smaller compared to the values of

Table 3. Average values of friction coefficient and standard deviations for WC-42CrMo4 sliding pair
Tabela 3. Średnie wartości współczynnika tarcia i odchylenia standardowe dla węzła ślizgowego WC-42CrMo4

Experiment no.	Hardness T [HRC]	Roughness Ra [μm]	Average coefficient of friction μ under different load Q		
			Q = 5 N	Q = 10 N	Q = 20 N
1.	42	0.24	0.098 ±0.0021	0.099 ±0.0023	0.100 ±0.0025
2.		0.14	0.096 ±0.0016	0.098 ±0.0014	0.099 ±0.0020
3.		0.04	0.090 ±0.0016	0.097 ±0.0015	0.098 ±0.0015
4.	32	0.24	0.101 ±0.0021	0.105 ±0.0025	0.105 ±0.0021
5.		0.14	0.094 ±0.0015	0.099 ±0.0018	0.1025 ±0.0015
6.		0.04	0.092 ±0.0014	0.096 ±0.0015	0.100 ±0.0025
7.	22	0.24	0.103 ±0.0023	0.107 ±0.0021	0.108 ±0.0015
8.		0.14	0.095 ±0.0018	0.100 ±0.0025	0.100 ±0.0028
9.		0.04	0.093 ±0.0020	0.097 ±0.0016	0.098 ±0.0025

series after grinding. The exampled courses of friction coefficients under the load of 5 N for selected material hardness and various surface roughnesses are presented in **Fig. 3**.

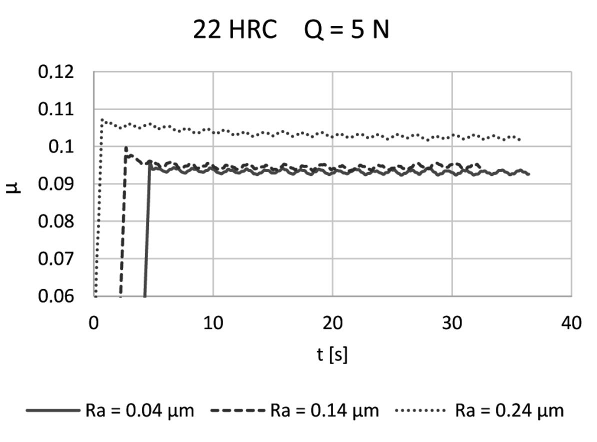


Fig. 3. Selected courses of friction coefficient of WC-42CrMo4 sliding pair with various surface roughness under load Q of 5 N (T = 22 HRC)
Rys. 3. Wybrane przebiegi współczynnika tarcia węzła ślizgowego WC-42CrMo4 o zróżnicowanej chropowatości powierzchni przy obciążeniu Q = 5 N (T = 22 HRC)

The reduction of the friction coefficient in the case of lapping process application for steel surface of element with a hardness of 32 HRC was approximately equal to 9% when the load was 5 N or 10 N. When the load was the greatest (20 N), the decrease in the friction coefficient of series after lapping or polishing was 5% compared to the values obtained for pairs with a grinding disc. Selected courses of the friction coefficient for sliding pairs with steel discs of 32 HRC hardness are presented in **Fig. 4**.

The smallest effect of the application of the additional finishing process was obtained with respect to friction pairs with a steel element improved thermally to the hardness of 42 HRC. The reduction in the coefficient of friction was less than 2% when the load was of 10 N or 20 N. This can be seen in **Fig. 5** where the courses of friction coefficient for sliding pairs with steel disc of a hardness equal to 42 HRC and a load of 20 N are presented. The courses of tested series are almost in the same line.

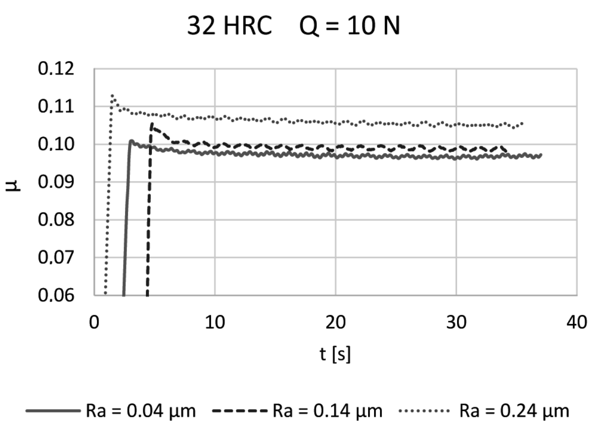


Fig. 4. Selected courses of friction coefficient of WC-42CrMo4 sliding pair with various surface roughness under load Q of 10 N (T = 32 HRC)
Rys. 4. Wybrane przebiegi współczynnika tarcia węzła ślizgowego WC-42CrMo4 o zróżnicowanej chropowatości powierzchni przy obciążeniu Q = 10 N (T = 32 HRC)

Relatively small improvement in the tribological characteristics expressed as a reduction in the coefficient of friction by 2–10% after applying additional finishing process was found, and it was quite similar for SiC ceramic implementation **[L. 1]**. To make it clear if the additional surface process is a reasonable solution in the case of the use of a ceramic element for counter-specimen, microscopic observations were done. **Figure 6** presents photographs of steel surfaces after tribological tests.

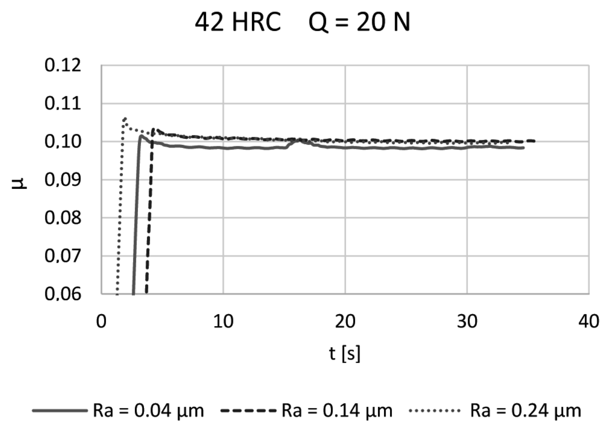


Fig. 5. Selected courses of friction coefficient of WC-42CrMo4 sliding pair with various surface roughness under load Q of 20 N (T = 42 HRC)

Rys. 5. Wybrane przebiegi współczynnika tarcia węzła ślizgowego WC-42CrMo4 o zróżnicowanej chropowatości powierzchni przy obciążeniu Q = 20 N (T = 42 HRC)

In **Fig. 6a**, there is a photograph of the steel disc surface after the lapping process and after tribological tests. There are visible wear tracks after contact with the steel ball and they look like scratches. Contrary, in **Fig. 6b**, the wear tracks on the ground surface are the flatten zones. That means that the mechanisms of wear of those series were different. In the case of the steel-steel sliding pair, the adhesive mechanism was dominant, although the load was small. In the situation of ceramic application in the sliding pair with steel disc of high roughness (Ra = 0.24 μm), only peaks were flatten and no scratches were observed. In the last photograph (**Fig. 6c**), the steel disc with small surface irregularities (Ra = 0.04 μm) after lapping that co-acted with WC element is presented. No signs of wear are observed on the steel surface mated with the ceramic element WC.

According to procedure of PS/DC 3^2 design, tests were carried out with the satisfactory repeatability of the experiments conditions, the effect of input factors was assessed, and the adequacy analysis of the regression equation were done. The results of statistical analysis according to PS/DC 3^2 design are presented in **Table 4**. Values of material hardness T and surface roughness Ra are coded as x_1 and x_2 and units are ignored in the statistical analysis.

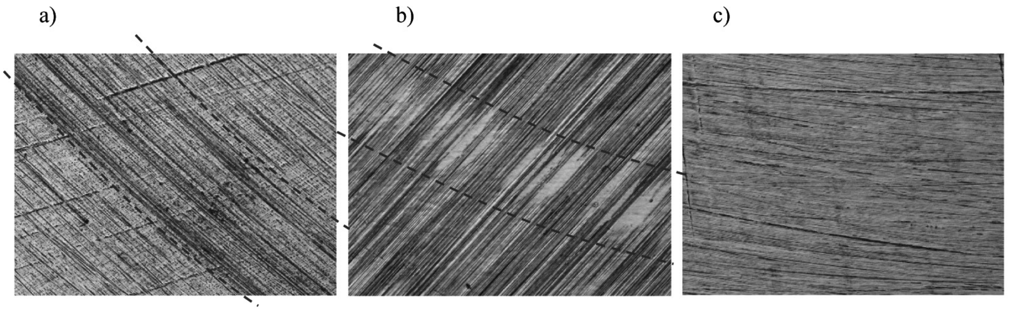


Fig. 6. Photographs of steel surfaces of material hardness 42 HRC after tribological tests under the load of 5 N: Ra = 0.04 μm co-acted with 100Cr6 (a), Ra = 0.24 μm co-acted with WC (b) and Ra = 0.04 μm co-acted with WC (c)

Rys. 6. Zdjęcia powierzchni stalowej tarczy o twardości 42 HRC po badaniach tribologicznych przy obciążeniu 5 N: Ra = 0,04 μm współpracującej z 100Cr6 (a), Ra = 0,24 μm współpracującej z WC (b) i Ra = 0,04 μm współpracującej z WC (c)

The dependencies between the coefficient of friction and surface roughness and material hardness under low and high loads are presented in the following formulas (3–4).

Under load Q = 5 N:

$$\mu = 0.0946 - 0.00148 \cdot \left(\frac{T-32}{10}\right) + 0.00464 \cdot \left(\frac{Ra-0.14}{0.1}\right) + 0.001483 \cdot \left(\frac{Ra-0.14}{0.1}\right)^2 \tag{3}$$

Under load Q = 20 N:

$$\mu = 0.1005 - 0.00163 \cdot \left(\frac{T-32}{10}\right) + 0.00289 \cdot \left(\frac{Ra-0.14}{0.1}\right) - 0.00124 \cdot \left(\frac{T-32}{10}\right)^2 + \\ +0.001822 \cdot \left(\frac{Ra-0.14}{0.1}\right)^2 - 0.00183 \cdot \left(\frac{T-32}{10}\right) \cdot \left(\frac{Ra-0.14}{0.1}\right) \tag{4}$$

Table 4. Statistical analysis of obtained results according to PS/DC 3[2] design for WC-42CrMo4 sliding pair
Tabela 4. Analiza statystyczna otrzymanych wyników według planu PS/DC 3[2] dla węzła ślizgowego WC-42CrMo4

Coded parameters $x_1 = \frac{T-32}{10}$ $x_2 = \frac{Ra-0.14}{0.1}$	Tribological test under load Q = 5 N		Tribological test under load Q = 20 N	
Repeatability $\alpha = 0.05$	$G_{kr} = 0.477$ $G = 0.173 < G_{kr}$ satisfactory		$G_{kr} = 0.477$ $G = 0.181 < G_{kr}$ satisfactory	
Input parameters effect	$b_{kr} = 0.00074$		$b_{kr} = 0.00087$	
b_0	$0.0946 > b_{kr}$	significant	$0.1005 > b_{kr}$	significant
b_1	$\lvert -0.00148\rvert > b_{kr}$	significant	$\lvert -0.00163\rvert > b_{kr}$	significant
b_2	$0.00464 > b_{kr}$	significant	$0.00289 > b_{kr}$	significant
b_{11}	$0.0001 < b_{kr}$	insignificant	$\lvert -0.00124 > b_{kr}$	significant
b_{22}	$0.001483 > b_{kr}$	significant	$0.001822 > b_{kr}$	significant
b_{12}	$\lvert -0.00072\rvert < b_{kr}$	insignificant	$\lvert -0.00183\rvert > b_{kr}$	significant
Assessment of adequacy of regression equation $\alpha = 0.05$	$F_{kr} = 2.576$ $F = 2.41 < F_{kr}$ adequate		$F_{kr} = 3.160$ $F = 0.626 < F_{kr}$ adequate	

After reorganization and calculation, the polynomials (3) and (4) are respectively (5) and (6):

$$\mu = 0.1483 \cdot Ra^2 + 0.004876 \cdot Ra - 0.000148 \cdot T + 0.0957466 \tag{5}$$

$$\mu = 0.1822 \cdot Ra^2 - 0.0000124 \cdot T^2 + 0.036444 \cdot Ra + 0.0008868 \cdot T - 0.00183 \cdot Ra \cdot T + 0.0843451 \tag{6}$$

In both cases of the applied load, the quadratic polynomials that described the relation between friction coefficient and parameters characterized sliding element were achieved. Under the low load of 5 N, the material hardness showed the linear relation, but the surface roughness had a stronger influence both in linear and quadratic dependencies. Under a higher load equal to 20 N, the effect of surface roughness is still greater than the material hardness, but both input parameters present the linear and quadratic relation with parameters characterized the sliding element. The interaction between input parameters is also an important factor that affects the coefficient of friction under greater load, which makes the assessment and prediction the tribological characteristics under greater loads more difficult.

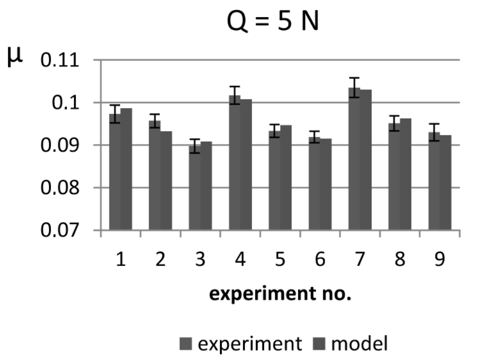
The regression functions give useful information about the dependencies between input parameters and output parameter. When analysing the polynomial (5), one can observe the evident influence of the roughness and smaller but also important effect of hardness. The lower the surface roughness and the greater hardness of the material, the lower is the coefficient of friction in the range of the input parameters variability under the load of 5 N. The dependency between parameters under the greater load of 20 N (6) is more complicated, and the polynomial is a useful tool to observe how the input parameters effect on output parameter. The surface roughness influenced in similar way (linear and quadratic) the friction coefficient like in (5), but as the equation coefficients in terms with Ra are greater, the influence of roughness is stronger than that under the lower load of 5 N. Concerning the material hardness, the influence is not simple like under load of 5 N (5) and under the higher load of 20 N, since the coefficient of friction values depend on specific values of the material hardness (6) from the variability range. Additionally, the greater the value of the interaction term, the lower is the coefficient of friction. The regression functions give important information about the influence of input parameters, which, in specific cases, could be difficult to find without statistical analysis. The advantage of the regression function is also the possibility to calculate the other output parameter values from the analysed range without doing additional experiments but under the condition that the model is adequate.

Graphs presenting values of friction coefficients for all analysed series under loads Q of 5 N and 20 N from the model and experiment are in **Fig. 7**.

The graphs indicate that the average and simulated values of friction coefficient are very similar. The series of the highest surface roughness are characterized with the greatest values of friction coefficients. At greater loads (**Fig. 7b**), the friction coefficient is higher than that under the low load (**Fig. 7a**). The obtained results are in a good accordance with those obtained by Svahn et al. **[L. 19]**. Authors of **[L. 19]** tested the sliding pairs with a-C:W coating with various roughness and found that the surface roughness influenced the friction substantially and also below the certain roughness of Rq equal to 0.12 µm the friction was less influenced by the surface roughness.

Generally, according to achieved results with smaller material hardness, the friction was higher for most of examined cases in the range of input parameters variability.

a)



b)

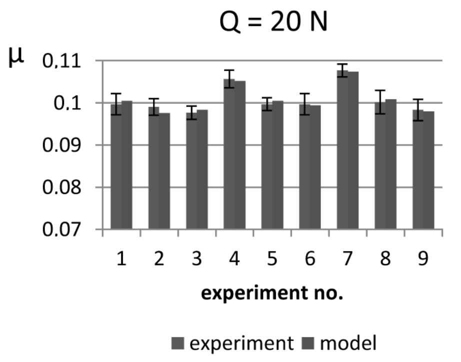


Fig. 7. Values of friction coefficient for all analysed series WC-42CrMo4 under load Q of: 5 N (a) and 20 N (b)

Rys. 7. Wartości współczynnika tarcia dla wszystkich analizowanych wariantów WC-42CrMo4 przy obciążeniu Q: 5 N (a) i 20 N (b)

CONCLUSIONS

It is reasonable to apply the ceramic elements instead of steel ones in sliding pairs under starved operating conditions. It prevents the adhesive wear of co-acting materials. The coefficient of friction is lower by approximately 30% with a ceramic element in comparison to that of the steel-steel sliding pair.

The surface roughness and material hardness of steel disc influenced the friction coefficient of sliding pair consists of steel and ceramic WC. An additional surface process like lapping allowed the reduction of the friction up to 10% when the material hardness of steel element was low. In case of the greater material hardness of steel discs, the friction coefficient reduction of sliding pair WC-42CrMo4 was smaller, and under the highest load, it was only 2%. The coefficient of friction also may be reduced by the increase of material hardness.

In the range of 22–42 HRC of material hardness of steel discs, on the ground steel surfaces, clear marks remained after contact with the ceramic ball. In traces of contact with the spherical element, deformations of the surface peaks after grinding were observed. On surfaces after additional processes like lapping or polishing, there were no visible wear tracks, which indicate that an additional technological process (lapping or polishing) allowed one to obtain the functionality of the surface as it is in the exploitation stage.

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