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Jerzy NAPIÓRKOWSKI*, **Krzysztof LIGIER****, **Magdalena LEMECHA*****, **Damian FABISIAK******

EVALUATION OF TRIBOLOGICAL PROPERTIES OF POWDER PAINT COATINGS USING THE BALL-CRATERING METHOD

OCENA WŁAŚCIWOŚCI TRIBOLOGICZNYCH MALARSKICH POWŁOK PROSZKOWYCH METODĄ BALL-CRATERING

Key words: ball-cratering method, paint coatings, coating tests.

Abstract The basic method for protecting industrial products against the destructive impact of the environment is to protect them with paint coatings. One of the important characteristics of paint coatings is their resistance to abrasive wear. The study tested three coatings with different granulations obtained by the electrostatic spraying method and then polymerised. The tests were carried out in two ways. Some of them were conducted in accordance with the standards in place at the paint manufacturer's laboratory, while the testing for abrasive wear resistance was conducted at a laboratory of the University of Warmia and Mazury in Olsztyn. The study involved measurements of thickness, gloss, scratching resistance, and wear using a rotational abrasion susceptibility tester and the ball-cratering method. Based on the obtained results, a different resistance to wear of particular coatings was found depending on the test stand. The study found the suitability of the ball-cratering method for the assessment of wear resistance of thin paint coatings. The proposed methodology omits the problem of measuring very small changes in weight, while the obtained wear results are linked to other characteristics of the surface layer.

Słowa kluczowe: metoda ball-cratering, powłoki malarskie, badania powłok.

Streszczenie Podstawową metodą zabezpieczenia przed destrukcyjnym oddziaływaniem środowiska wyrobów przemysłowych jest ich zabezpieczanie powłokami malarskimi. Jedną z istotnych cech charakteryzujących powłoki malarskie jest ich odporność na zużycie ścierne. Badaniom poddano trzy powłoki o różnej granulacji uzyskane metodą natrysku elektrostatycznego, a następnie poddane procesowi polimeryzacji. Badania przeprowadzano dwutorowo. Część z nich przeprowadzono, zgodnie z obowiązującymi normami, w laboratorium producenta farb. Natomiast badanie odporności na zużycie ścierne wykonano w laboratorium Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. Badania obejmowały pomiar grubości, połysku, odporności na zarysowania oraz zużycia rotacyjnym testerem ścieralności i metodą ball-cratering. Na podstawie uzyskanych wyników stwierdzono odmienną odporność na zużycie poszczególnych powłok w zależności od stanowiska badawczego. Stwierdzono przydatność metody ball-cratering do oceny odporności na zużycie cienkich powłok malarskich. Zaproponowana metodyka omija problem pomiaru bardzo małych zmian masy, zaś uzyskane wyniki zużycia są powiązane z pozostałymi charakterystykami warstwy wierzchniej.

INTRODUCTION

Powder coating is currently the most commonly used method for protecting metal surfaces. Apart from ensuring an appropriate colour, powder paint primarily protects the surface against adverse factors, e.g., corrosion, chemicals, UV radiation, or abrasive material impact. The most commonly used types of powder paints include epoxy, epoxy and polyester, polyurethane, and polyester **[L. 1]**. Powder coatings are usually epoxy resin- or polyester-based paints. They

* ORCID: 0000-0003-2953-7402. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, ul. Michała Oczapowskiego 11, 10-736 Olsztyn, Poland, tel. 089 523-34-63.
** ORCID: 0000-0003-1348-7068. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, ul. Michała Oczapowskiego 11, 10-736 Olsztyn, Poland, tel. 089 523-34-63.
*** ORCID: 0000-0003-3414-4099. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, ul. Michała Oczapowskiego 11, 10-736 Olsztyn, Poland, tel. 089 523-34-63.
**** KAMET Sp. z o.o., Piątki 88, 13-100 Nidzica.

are characterised by a significant, broadly understood resistance and are suitable for industrial applications, e.g., structural components exposed to high loads and aggressive chemicals, with the former resin used indoors and the latter outdoors. The properties of powder paint coatings are determined in accordance with numerous relevant standards. The basic properties of paint coatings are described by the following characteristics:

- Geometrical – thickness, surface unevenness;
- Physical – adhesion, hardness, elasticity;
- Operational – abrasion resistance, impact resistance, corrosion resistance; and,
- Decorative – colour, gloss, external appearance.

One of the basic characteristics of a painted coating is the resistance to tribological wear that can occur while using a surface under conditions of dustiness, the transportation of abrasive agents, cleaning, or friction due to accidental contact with a hard object.

Testing for wear resistance requires that conditions simulating the expected operation of the coating be provided. The studies conducted to date most frequently used a variety of simple sets of abrasive parts on standardised or test stands **[L. 2]**.

The solutions of fundamental importance are those based on the abrasion of coating by abrasive parts falling onto a flat solid surface such as a metal or glass panel, e.g., using a Gardner device **[L. 3]**. Abrasive material falls gravitationally from a specified height through a pipe leading onto a painted panel until the moment the coating was worn through. The abrasion resistance of a coating is characterised by the amount of abrasive material per coating thickness unit **[L. 4, 5]**. Both silica sand and silicon carbide can be used. The presented method is applied for the assessment of the durability of both thin single- and multiple-layer coatings. A variation of the presented test methodology is the use of compressed air to increase the abrasive material impact intensity **[L. 4]**. Since the flow of abrasive material is intensified by the rush of air, the abrasion rate is significantly higher than that obtained when the abrasive material falls down freely.

In industrial practice, testers using loaded rubber or abrasive wheels moving around the tested coating are commonly applied **[L. 6]**.

Resistance to abrasion is calculated in three ways: as a loss of weight following a specified number of abrasion cycles, as a loss of weight per cycle, or as a number of cycles required to remove a unit amount of coating thickness. The main disadvantage of this methodology of abrasion testing is the possibility for quick perforation of the paint coating and thus an increase in the loss of weight on the substrate, which results in significant errors in calculations of the paint weight loss. Moreover, the abrasive disc itself changes its geometrical or abrasive properties during testing. This may result in poor repeatability of the test results and difficulty in comparing the values reported by different laboratories. The implant of abrasive particles in the paint during the abrasion test also contributes to the occurrence of errors.

Polish standards provide three methods for assessing resistance to abrasive wear: a rotating wheel covered with abrasive paper, a rotating rubber disc, and testing on samples in a reciprocal motion **[L. 7–9]**.

An abrasion test in a macro scale was also developed, which enables the measurement of wear resistance of the surface areas of the material based on micro-chips **[L. 10]**. During the tests, the coating penetration depth is less than 30 μm. A 'pin-on-disc' tribological system was used. The value subjected to assessment is that of the load resulting in paint inconsistency or damage.

The basic disadvantages of the methods described above include the following:

- The poor repeatability of test results, and difficulties in comparing the values reported by different laboratories;
- Resistance to abrasion is calculated as the weight loss following a specified number of abrasion cycles. Aggressive abrasion process, in most functional solutions used in test stands, rather quickly perforates the paint coating and results in a loss of weight on the substrate, which leads to errors in calculations of the paint weight loss; and,
- The possibility of pressing abrasive particles into the paint coating during the abrasion test results in a change in the friction process course.

In view of the above-mentioned disadvantages, new test methods are being sought. Among others, a method involving a ball rotating in a suspension of small abrasive particles was applied **[L. 11]**. Tests are carried out on a sample area smaller than 4 mm^2 and the maximum trace depth of 30 μm. This technique omits the most common problem encountered while testing on the wear of thin coatings, namely, the measurement of very small changes in the weight or volume. It is applied only for small samples and thin coatings.

Taking the above into account, an attempt was made to verify the suitability of the ball-cratering method which is often referred to as the „ball crater" method. **[L. 12, 13]**.

The aim of the study is to compare the wear of polyester paint coatings with different structures under the conditions of a rotating abrasive wheel and the „ball-cratering" method.

TEST METHODOLOGY

The samples prepared for the study were cut out from cold-rolled low-carbon steel (0.12% C, 0.60% Mn) of the DC01 grade marked 1.0330 (in accordance with PN-EN 10152:2017-03), intended for cold forming. The samples were painted at the manufacturer's laboratory with polyester powder paint for external applications. Polyester paints are among the most commonly used types of powder paints. They are characterised by good mechanical and chemical resistance and do not change colour under the influence of UV radiation. The basic component of the paint includes cross-linking polyester resins, i.e. liquid solutions of polyester and cross-linking monomers. Other additives include a pigment that gives the coating its colour, additives aimed at providing appropriate gloss of the paint layer being applied, and fillers. These are substances in the form of grains or powder, insoluble in the binder, used to modify or affect certain physical characteristics. A filler controls paint viscosity and abrasion resistance, has an effect on the degree of gloss, provides thixotropy, and prevents the so-called phase separation of the paint.

The paints were applied using the powder coating technology by high-voltage-charged electrostatic spraying method. Prior to the application of a coating, the samples were degreased. After the application, the coating was polymerised. To this end, the paint layer was hardened by heating in a convection-type furnace for 10 minutes at 185°C (the value range of 160–200°C). According to the manufacturer's information, the coating obtained in this way is resistant to corrosion, chemicals, mechanical damage, and high temperature.

Three types of samples with surfaces differing in the thickness, gloss, and surface structure were prepared **(Fig. 1)**.

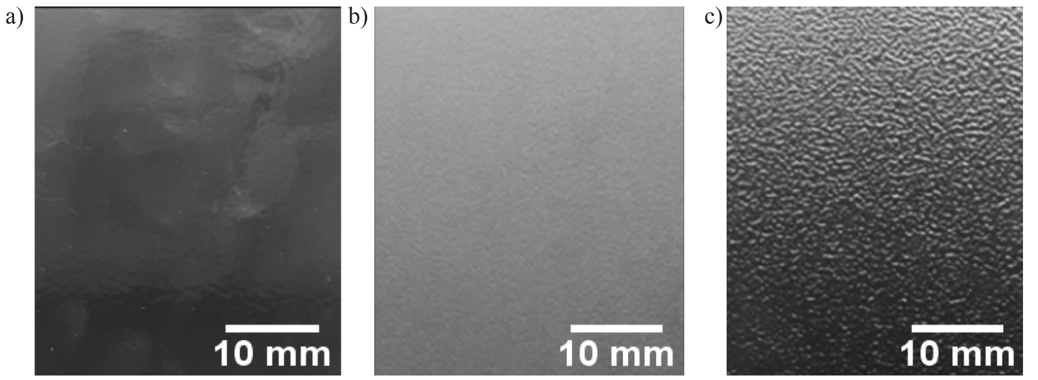

Fig. 1. DC01 steel samples covered with the ested paint coatings: a) smooth granulation, b) fine granulation, c) coarse granulation

Rys. 1. Próbki stali DC01 pokryte badanymi powłokami malarskimi: a) granulacja gładka, b) granulacja drobna, c) granulacja gruba

The obtained coatings were subjected to laboratory testing in order to determine:

- Thickness,
- Gloss,
- Resistance to scratching, and
- Resistance to abrasion.

The test for thickness was conducted using a MiniTest 700 series coating thickness gauge that applies the magnetic induction-based method for measuring paint coating thickness. The test for gloss was conducted in accordance with standard PN-EN ISO 2813:2014:11 using a TQC Polygloss gloss meter that enables the measurement of coating gloss at an angle of 60° and 85°. The selection of a measurement angle is determined by the type of the tested surface. The coating gloss is usually measured at an angle of 60°, while for materials with low gloss, a measurement at an angle of 85° is recommended.

The test for scratching resistance was conducted in accordance with standard PN-EN ISO 1518-1:2011 using a BDG-520 automatic scratch tester. For the abrasion wear susceptibility testing, a DT-523 rotational tester was used **(Fig. 2)**.

Fig. 2. DT-523 rotational abrasion tester

Rys. 2. Rotacyjny tester ścieralności DT-523

A flat sample with dimensions of 100 x 80 x 4 mm was mounted on a rotating table, and then abrasive wheels were pressed against its surface. The test result was based on the measurement of the sample weight loss after the performance of a specified number of revolutions, expressed in grams. Such a test is in line with standards ASTM D44060-14 [6] and PN-EN ISO 77784-1:2008 **[L. 7]**.

The following test parameters were applied:

- A platform speed of 60 revolutions per minute,
- A load of 500 g,
- Number of revolutions – 200, and

- Calibrase CS-10 abrasive wheels – averaged abrasive properties used as standard in order to reproduce the abrasion exposure,

The assessment of weight loss was carried out using laboratory scales with an accuracy of 0.0001 g.

The assessment of tribological properties of the tested coatings by the ball-cratering method was carried out using a T-20 tribometer. During the tests, samples with dimensions 30 x 25 x 4 mm were used while applying the following friction parameters:

- A load on the contact point of 10 N,
- A ball diameter of 24.4 mm,
- A ball rotational speed of 80 revolutions per minute, and
- A slide velocity of 0.11 m/s.

A ball with a diameter of 24.4 mm (1”) made from 100Cr6 steel with the following chemical composition was used: 0.95–1.1% C, 0.25–0.45 Mn, 0.15–0.35 Si, and 1.3–1.35 Cr. The tests were carried out in variants without coating perforation and without the use of abrasive material. Assessment of the wear rate was conducted on the basis of the Archard’s relation that links the loss in volume with the wear rate as well as the sliding distance and the load on the friction node:

$$V = K_c S N \tag{1}$$

where
V – the volume of material removed due to friction, K_c – the rate of coating abrasive wear, S – sliding distance, N – normal load.

The volume removed due to friction was calculated on the basis of the obtained crater dimension using the following formula:

$$V = \pi \frac{b^4}{64R} \tag{2}$$

where
V – the volume of material removed due to friction, R – ball radius, b – crater diameter.

Taking into account Formulas (1) and (2), the coating wear rate was determined using the following formula:

$$K_C = \pi \frac{b^4}{64RSN} \tag{3}$$

where
K_C – wear rate, b – crater diameter, R – ball radius, S – friction distance, N – normal load on the node.

Crater dimensions were determined by means of observation and measurements using a HUVITZ HRM-35 microscope, in order to determine the significance of differences between the following:

- The mass wear of the coatings tested using a rotational abrasion tester,
- Values of the wear rate K_c of the coatings tested using a T-20 tester, and
- Friction coefficient values.

For each structure type, a null hypothesis H_0 about the lack of differences between the obtained values for constant friction parameters was adopted, in relation to an alternative hypothesis H_1 about the occurrence of significant differences in the values obtained for particular coatings. Where the null hypothesis was rejected in favour of the alternative one, Duncan’s test was used to distinguish homogeneous groups.

TEST RESULTS

The average thickness of a coating ranged from 100.3 µm for the smooth coating, through 113.4 µm for the fine coating, to 127.8 µm for the thick-structured coating. The values of obtained gloss are presented in **Table 1**. The coarse coating gloss was not measured due to the measurement limitations of the instrument.

Table 1. Results of gloss measurement
Tabela 1. Wyniki pomiaru połysku

Coating structure	Measurement angle [°]	Average gloss value (GU)
Smooth	60	91.65
Fine	85	2.60

The smooth coating was characterised by the lowest resistance to surface scratching. In this case, the coating was already scratched under the load of 1 N. The fine-structured coating was characterised by the highest resistance to scratching; it was scratched under the load of 8 N. The coarse-structured coating was less resistant to scratching than the fine-structured coating. In this case, a force of 7 N was required to make a scratch.

Of all the tested samples, the fine coating was characterised by the worst anti-wear properties. After carrying out the variance analysis, *post-hoc* tests were conducted in order to find differences between the loss of weight and the rate of wear of the tested materials. Statistically significant differences were found between the coating wear values **(Table 3)**. The weight loss in the fine coating was greater by 68% than the weight loss in the coarse coating, and by 96% than the smooth coating. The obtained relationships are illustrated by the view of the surfaces obtained after the wear process **(Fig. 3)**. The smooth surface with the highest gloss value is characterised by uniform wear traces without visible tear-outs. However, other surfaces are characterised by numerous discontinuities of the friction trace, resulting from torn out sections of paint coating. No relationships between the coating thickness, resistance to scratching, and resistance to abrasive wear were noted.

Results of tests for wear rate using the ball-cratering method are provided in **Table 4**. Examples of craters for particular coatings are characterised on **Fig. 4**.

Table 2. Summary of coating weight loss depending on the coating structure

Tabela 2. Zestawienie ubytku masy powłok w zależności od struktury powłoki

Coating structure	Sample weight prior to testing [g]	Sample weight after testing [g]	Weight loss [g]
Smooth	81.8578	81.8457	0.0121
Fine	82.2228	82.1991	0.0237
Coarse	82.0224	82.0083	0.0141

Table 3. Results of the Duncan's test analysis of differences between mass wear values

Tabela 3. Wyniki analizy testem Duncana różnic między wartościami zużycia masowego

Duncan's test; Homogeneous groups, alpha = .05000				
Coating structure	Weight loss [g]	1	2	3
Smooth	0.0120	****		
Coarse	0.0141		****	
Fine	0.0236			****

a)

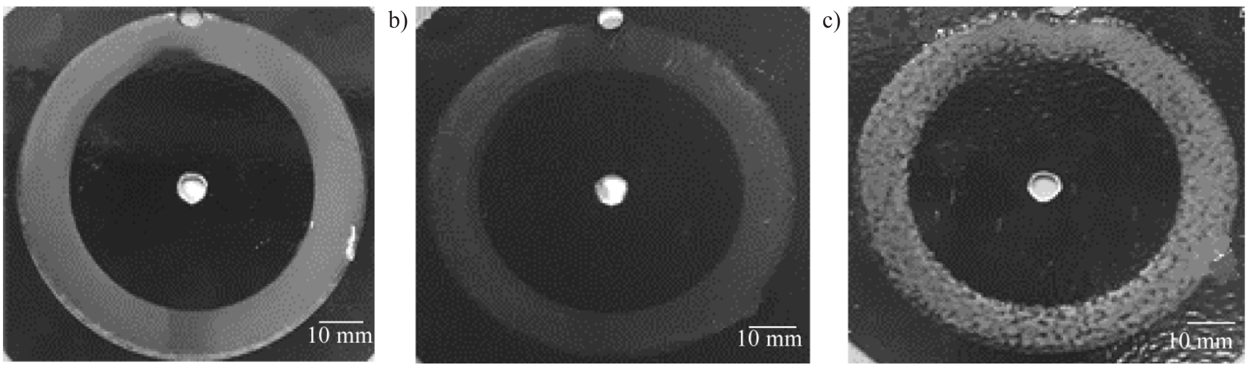

Fig. 3. A view of the coating surface following abrasion in a rotational abrasion tester: a) smooth coating, b) fine coating, c) coarse coating

Rys. 3. Widok powierzchni powłoki po ścieraniu w rotacyjnym testerze ścieralności: a) powłoka gładka, b) powłoka drobna, c) powłoka gruba

Table 4. Characteristics of coating wear by the ball-cratering method

Tabela 4. Charakterystyka zużycia powłok metodą ball-craterring

Coating structure	Friction force value [N]	Friction coefficient value	Wear rate KC [$m^3N^{-1}m^{-1}$]
Smooth	5.81	0.581	5.43585E-05
Fine	3.04	0.304	8.33595E-06
Coarse	6.70	0.670	3.57315E-05

a)

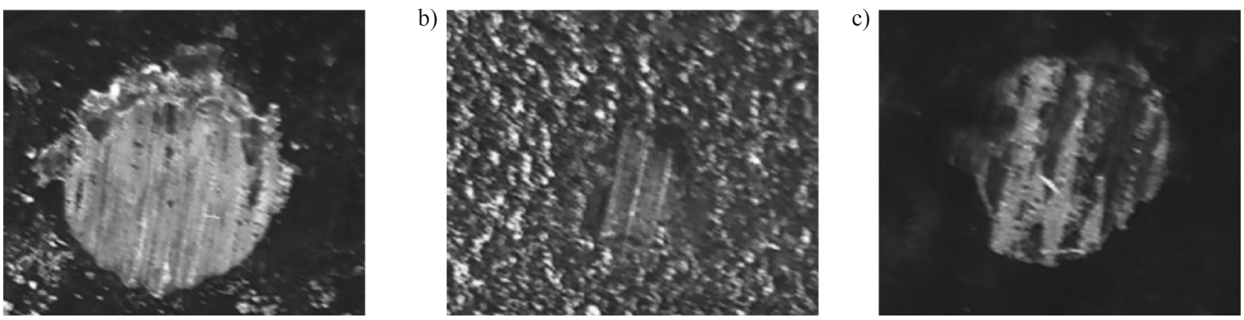

Fig. 4. A view of examples of craters obtained after the test: a) smooth coating, b) fine coating, c) coarse coating

Rys. 4. Widok przykładowych kraterów uzyskane po badaniu: a) powłoka gładka, b) powłoka drobna, c) powłoka gruba

The lowest abrasive wear rate was obtained for the fine-structured coating, and it is lower by more than three times than the coarse-structured coating, and more than five times than the smooth coating. It was found that the obtained values differed significantly between one another **(Table 5)**.

Table 5. Results of the Duncan's test analysis of differences between K_C wear rate values

Tabela 5. Wyniki analizy testem Duncana różnic między wartościami intensywności zużycia KC

Duncan's test; Homogeneous groups, alpha = .05000				
Coating structure	Wear rate K_c Average	1	2	3
Fine	0.000008	****		
Coarse	0.000036		****	
Smooth	0.000054			****

The obtained results indicate that, with an increase in the minimum force required to scratch a coating, its resistance to abrasive wear increases. The tests showed significant differences in the friction coefficient values for the tested coatings **(Table 6)**. The time until the smooth coating was worn through was 25 minutes, and the friction distance was 158 m. On the crater formed in the sample, a complete wear-through of the coating to the native material became visible. The testing on samples with a fine structure lasted for 60 minutes, and the coating was not worn through. The friction distance amounted to 378 m. For this coating, the lowest friction coefficient of 0.308 was obtained. Presumably, for this type of coating, polytetrafluoroethylene or Teflon (a friction coefficient of 0.08–0.1) contained in the paint is characterised by the best tribological properties. **Figure 4** shows a minimum disturbance to the surface layer structure. The coarse-structured coating was worn through after 20 minutes, and the friction distance was 126 m. It is noticeable that the trace of smooth coating wear was characterised by a greater area than the trace in the coarse-structured coating. On the other hand, the highest friction coefficient was noted for the coarse-structured coating; it was higher by only 0.089 than the smooth coating characterised by high gloss. Therefore, there was no relationship between the friction force and the coating gloss.

Table 6. Results of the Duncan's test analysis of differences between the friction coefficient values

Tabela 6. Wyniki analizy testem Duncana różnic między wartościami współczynnika tarcia

Duncan's test; Homogeneous groups, alpha = .05000				
Coating structure	Friction coefficient value	1	2	3
Fine	0.3044	****		
Smooth	0.5818		****	
Coarse	0.6625			****

SUMMARY

Two new methods for assessing wear resistance of three types of paint coatings with different external structure were applied. Depending on the test stand type, significantly different results were obtained. As for the testing on coatings by the abrasive wheel method (in accordance with PN-EN ISO 7784-2:2006) moving around the tested coating, it was the smooth coating that was characterised by the best anti-wear properties, which was followed by a coarse and a fine coatings. The differences in weight loss were relatively small and amounted to 0.0116 g. A different order of wear resistance was obtained for the ball-cratering method. The smallest wear was found for the fine-structured coating characterised by the thickness of 113.4 µm, and it had the lowest friction coefficient and the highest scratching resistance. The wear rate coefficient K_c value was six times lower for the fine coating than for the smooth coating.

The proposed test methodology omits the measurement of very small changes in weight, which is the most common problem encountered while carrying out tests for thin paint coating wear. Moreover, at the moment when the paint coating was worn through, there is a possibility of interrupting the friction process. In this way, an increase in the accuracy of wear measurement is obtained through the elimination of substrate loss. It also extends the measured values in relation to the requirements provided in standards to include the friction coefficient values.

An unambiguous statement on the suitability of the presented method for testing paint coatings under industrial conditions will be possible after the extension of research to include other paint coatings. The introduction of abrasive material to the tribological pair is also envisaged. Such conditions will better reflect the actual course of the use of paint coatings in an atmospheric environment.

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