A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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WEAR RESISTANCE OF ALUMINIZED STEEL PLATES

ODPORNOŚĆ NA ŚCIERANIE ALUMINIOWANYCH TAŚM STALOWYCH

The results of the abrasion resistance measurements of aluminized steel strips are presented in the hereby paper. Steel strips of DX52D+AS120 grade, before and after a heat treatment at temperatures of 200-1000°C for 1 – 5760 minutes, were tested. Tests of the abrasion resistance were carried on in a specially built device: rotating disk – sample performing a plane-rotary motion, with an application of a lubricating medium. Examinations of the abrasion resistance were also performed by means of the block-on-ring tester. Estimations of a coating mass loss, roughness and thickness changes were carried on. The obtained results are illustrated by diagrams and macro- and micro-observations. Phase analysis investigations were also performed on samples selected after the abrasibility testing. The range of the heat treatment parameters – after which the Al-Si coating increased its abrasion resistance – was estimated.

Keywords: aluminized steel plate, abrasion resistance, coating, roughness, X-ray phase analysis

W artykule przedstawiono wyniki badań odporności na ścieranie aluminiowanych taśm stalowych. Badaniom poddano taśmy stalowe z gatunku DX52D+AS120 przed i po obróbce cieplnej w temperaturze 200-1000°C w czasie 1min-5760min. Wykonano badania odporności na ścieranie w specjalnie przygotowanym urządzeniu typu obracająca się tarcza – próbka, wykonująca ruch posuwisto-zwrotny, przy zastosowaniu środka smarującego Zrealizowano także badania odporności na zużycie cierne za pomocą testera typu rolka-klocek. Dokonano oceny ubytku masy, zmian chropowatości i grubości powłoki. Wyniki badań zobrazowano za pomocą wykresów oraz makro i mikro obserwacji. Przeprowadzono także badania analizy fazowej na próbkach wytypowanych po badaniach ścieralności. Określono taki zakres parametrów obróbki cieplnej, po której następuje wzrost odporności na ścieranie powłoki Al-Si.

1. Introduction

Aluminized steel strips due to their properties, strength and plasticity, warranted by the base material as well as corrosion resistance guaranteed by the coating, found applications in many industrial sectors, among others in building, motorization, heat engineering, household appliances production. Standard [1] determines steel grades, which can be aluminized. Steel is covered either by pure aluminum or by silumin containing 8-11% of silica. Silumin coatings are more advantageous as compared to the aluminum ones. Their melting temperature (app. 580°C) is lower than that of pure aluminum, which is beneficial for technical aspects of their production. Such coatings have a transient layer of Al-Fe-Si, not very thick, being formed due to diffusion processes between the base material and coating, and this layer increases compliance of strips with plastic working. Requirements concerning steel strips with Al-Si coating are given in [2-3]. Several investigations concerning coatings formation, heat and plastic treatments of aluminized steel strips and their application are presented in papers [4-15].

An essential feature, still limiting the application of such strips and their products, is a low abrasion resistance of the Al-Si coatings in contact with forming tools as well as with external factors influencing the coating during the exploitation. Thus, the application of the proper lubricating-cooling medium during plastic treatment of such strips seems obvious. However, using of such mediums during the exploitation is limited and sometimes even impossible.

In order to improve radically the Al-Si coating abrasion resistance the simulation, multi-variant heat treatment, leading to the controlled structural and chemical composition changes of the coating (due to a mutual diffusion of coating and base components) – determining changes of its properties – was designed and performed.

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The strips, after the heat treatment, were subjected to two-stage abrasibility examinations by means of the specially designed and built (according to the author's concept) device, as well as by the tester T-05 allowing to perform abrasion wear tests measurements – in accordance with the methods determined in the American Standards. Other methods of measurement of abrasion resistance are presented in papers [16-18].

Additionally the X-ray diffraction investigations were performed in order to determine the coating phase composition after the heat treatment. The obtained results are presented as graphs of the sample mass loss after an abrasion in diagrams and as microscopic observations.

2. Experimental technique

Steel strips of DX52D+AS120 grade, of a thickness app. 1.5mm, with the Al–10%Si coating of a thickness app. 18-23μm were chosen for testing. The chemical composition of the aluminized steel strip base is shown in Table 1. Determinations of the chemical composition was performed by the optical emission spectrometry method by means of SPECTROLAB M7.

TABLE 1

Chemical composition of strip (wt.%)

C	Mn	Si	P	S	Cr	Ni	Nb	Cu	Al	Fe
0.004	0.14	0.006	0.009	0.011	0.02	0.022	0.014	0.017	0.045	Bal.

Samples of dimensions 250×250 mm were cut from steel strips. Then samples were heated in a chamber furnace in the air atmosphere at temperatures 200 – 1000°C, for 1 – 5760 minutes. After heating, the samples were air cooled outside the furnace until a temperature of 23±2°C was achieved.

The abrasion resistance tests were performed for samples after the heat treatment. Tests were performed in the specially designed and constructed stand (Fig. 1). The Al-Si coated strip samples, before and after the heat treatment, were cut for dimensions of 150×150mm. Four openings were drilled in each sample for fixing it to the disk. Samples were degreased in C_2H_5OH solution in the ultrasound washer, dried in the laboratory dryer and weighted with the accuracy of four decimal places by means of the laboratory scale. Then samples were fixed to the disk. The counter sample, in a form of a roll (of a diameter 12mm) ended with a semicircular cap, constituted the Hardox 500 steel.

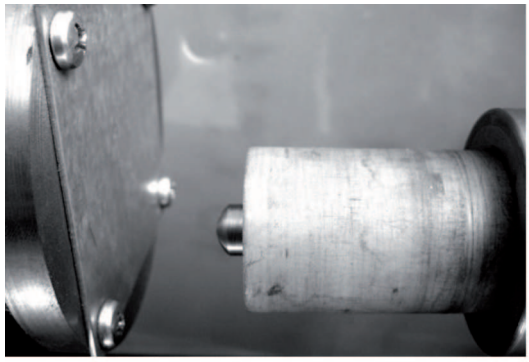


Fig. 1. Device for the abrasion resistance testing

Investigations were performed in the described below way. The steel sample was put into an angular motion with a velocity of 9rot/min. The counter sample was pressed into the sample with a constant pressure of 200N. During the angular motion of the coated sample its counter sample was doing a plane-rotary motion with an amplitude of 10mm. Tests were performed under the fluid friction conditions. As a lubricating-cooling medium 10% water solution of the emulsifiable oil Emulgol ES12 was used. One test cycle took 2 minutes. In order to determine the mass losses all samples were weighted before and after the test. Changes of the coating surface roughness, before and after an abrasion, were determined in the contact place of the sample with the counter sample. The coating roughness tests were performed on one side of the sample. Each time the average value of the surface roughness parameters R_a and R_z was calculated from ten measurements. The coating surface roughness after an abrasion was measured in the direction perpendicular to the sample motion. Measurements were done by means of the Form Talysurf device of the Taylor Hobson Company. The obtained results are presented in diagrams. For the possibility of comparisons the tests were also carried on for samples without the heat treatment. For each type of test three samples with and without the heat treatment were used.

The obtained results are presented as graphs of the sample mass loss after an abrasion in diagrams and as microscopic observations of the coating surface after abrasibility tests. Observations were carried out by MULTIZOOM AZ 100 microscope of the Nikon Company. Next the abrasion resistance tests were performed by using the T-05 tester (Fig. 2).

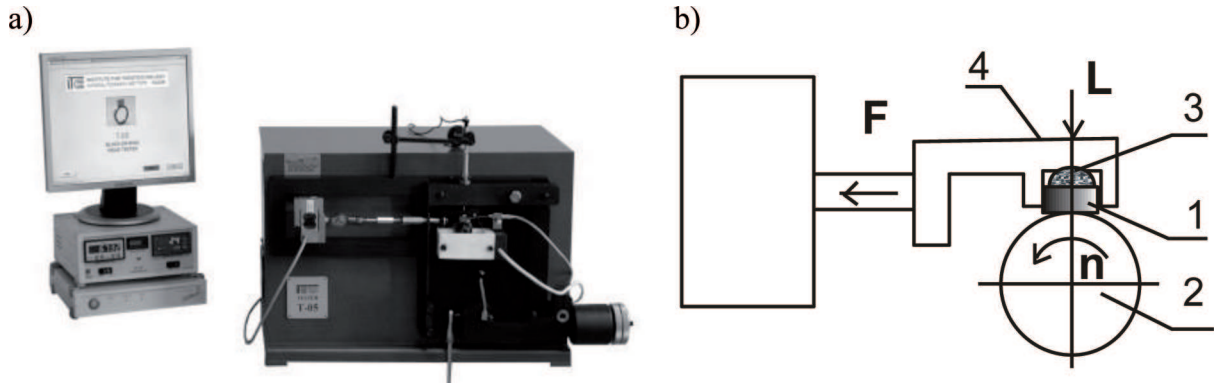


Fig. 2. Block-on-ring T-05 wear tester: a) view of tester, b) schematic of tester

This tester enabled performing tests in accordance with the methods determined in Standards ASTM D 2714, D 3704, D 2981 and G 77.

The sample (1) was mounted in a sample holder (4) equipped with a hemispherical insert (3) ensuring proper contact between the sample and a rotating ring (2). The wear surface of the sample was perpendicular to the pressing direction. Double lever system input the load L, pressing the sample to the ring with the accuracy of ±1%. The ring rotated with a constant rotating speed. The wear tests conditions chosen for the current investigations were:

- tested samples – rectangular as-infiltrated specimens 20×4×1,5mm,
- counterpart (rotating ring) – ϕ 49.5×8mm, heat treated steel, 55 HRC,
- dry sliding,
- rotational speed – 136rev./min.,
- load – 67N,
- sliding distance – 250m.

The measured parameters were:

- loss of sample mass,
- friction force „F" (used to calculate the coefficient of friction).

The results are presented in diagrams as the friction force and the abrasion depth versus the testing time – for samples before and after the heat treatment – and also as graphs of mass loss of samples dependence on the heat treatment parameters.

To determine the coating phase composition after the heat treatment the X-ray diffraction examinations were performed by means of the D500 Kristalloflex X-ray diffractometer of the Siemens Company. A monochromatic radiation of a copper anode lamp was utilised (λ = 1.54A). Diffraction lines were recorded in the 2θ angle range from 17° to 125° by the step-count method with the 2θ angle jump being 0.02°. The Bragg-Brentano geometry was applied during measurements. Diffractograms were drawn in the 2θ angle range from 20° to 80°, omitting high-angle reflections since it enabled a more distinct separation of peaks situated close to each other.

The X-ray diffraction (XRD) investigations allowed to determine and compare the coating phase composition, simultaneously explaining the reasons of the coating diversified abrasion resistance.

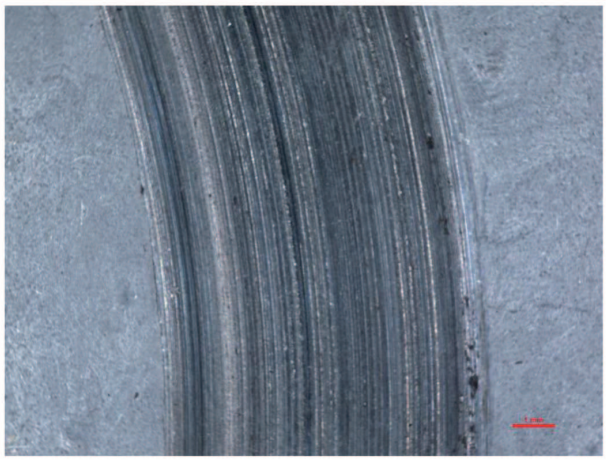
3. 3. Results and discussion

3.1. Abrasion resistance examinations

The observation results of the selected coating surfaces after the heat treatment and abrasibility tests are presented in Fig. 3.

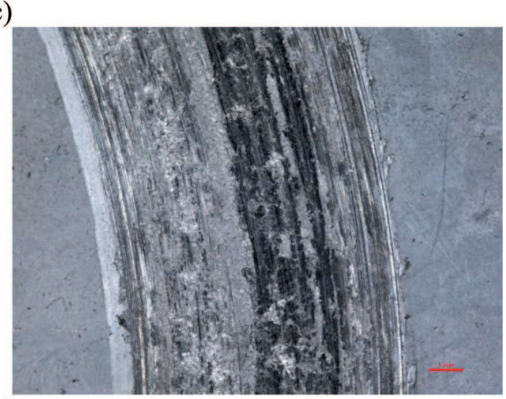
At the coating observation, apart from the abrasion zones, changes in the coating appearance from bright and glossy (Fig. 3a-d) to partially (Fig. 3e-h, j, l) or completely dark and matt (Fig. 3i, k, m-o) attract attention. The results of observations of the coating surface – after an abrasion - are highly correlated with the coating appearance.

a)



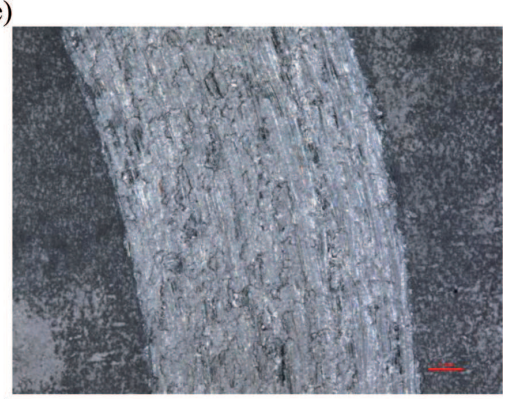
b)

c)

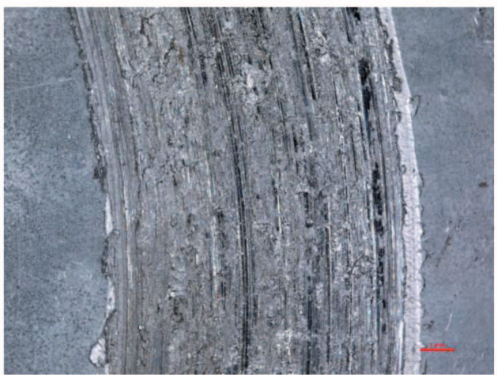


d)

e)



f)



g)

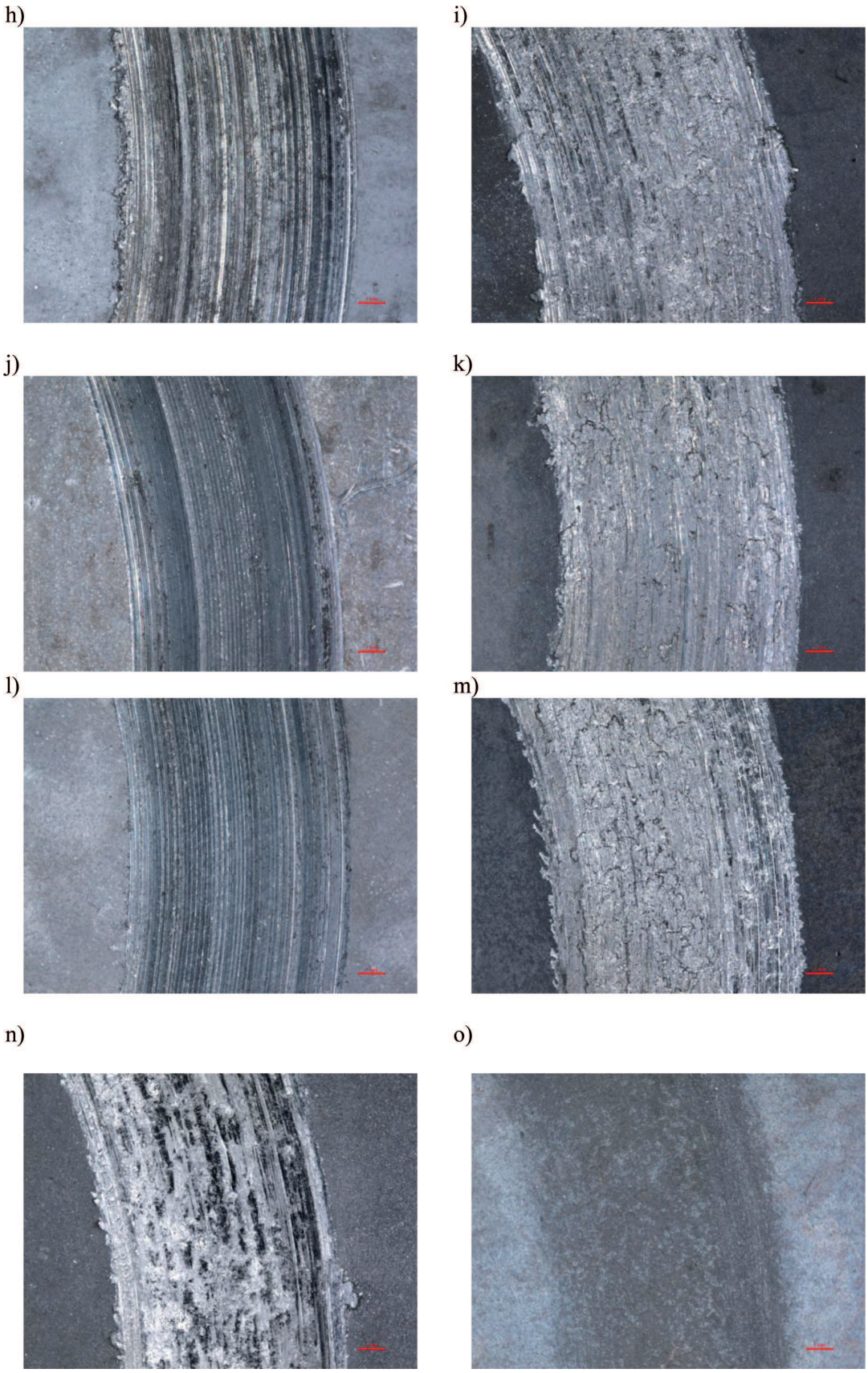


Fig. 3. The observation results of the selected coating surfaces after the heat treatment and abrasibility tests
a) Initial state, b) 200°C-180min., c) 200°C-5760min., d) 500°C-180min., e) 500°C-1440min., f) 600°C-5min., g) 600°C-30min., h) 700°C-5min., i) 700°C-10min., j) 800°C-2min., k) 800°C-5min., l) 900°C-1min., m) 900°C-5min., n) 1000°C-2min., o) 1000°C-5min

During an abrasive wear of a relatively soft material the mechanisms of grooving and microcutting are dominating and mutually competing. Gradual passing from one wear mechanism to another was occurs and in consequence grooving and microcutting of various proportions coexist in a wide range (Fig. 3a-d). Such influence is accompanied by a minimal or small coating mass loss, presented in Fig. 4.

A characteristic adhesive wear occurs in the samples, which surface became dark and matt under the heat treatment influence. Hard, but very brittle, particles present on the coating surface are torn off during an abrasion process. A continuation of the abrasion process intensifies the adhesive sticking, sinking of particles deep inside the coating, mixing with it and in consequence the coating fragments are tearing off and craters are formed (Fig. 3i, k, m-n). These tribologic effects cause an uneven, deep wearing out of a material, which is proofed by the mass loss results. The coating surface roughness results, which reflect the surface unevenness after abrasion, are shown in Fig. 5-6. Examinations are accompanied by acoustic effects intensifying with progressing tests, giving evidence to a high and constantly increasing friction coefficient. When the coating surface after the abrasibility tests is in certain areas dark and in other bright it means, that two or even three mechanisms of wear are simultaneously occurring: adhesive in darker places while microcutting and grooving in brighter ones (Fig. 3e-h, j, l).

Completely different wearing character occurs in the samples after the heat treatment at a temperature of 1000°C for 5 minutes (Fig. 3o). None of the previously identified wearing mechanisms occurs during the abrasion. The coating surface becomes smooth, micro-unevenness is removed, no scratching or craters are seen and none acoustic effects are heard – during the tests. On the other hand, the counter sample surface (Hardox 500 steel) undergoes some wearing in contact with the coating. This indicates the complete change of the coating hardness after the heat treatment. Surface and structural changes of the coating are confirmed by mass loss tests, roughness, friction depth and force.

The obtained results of the mass loss in dependence of the heat treatment conditions are illustrated in Fig. 4.

The diversified mass loss after the abrasibility tests correlates with the surface appearance changes resulting from the heat treatment conditions – temperature and time (Fig. 4). The biggest mass loss occurs for a heating temperature of 900°C (for 10 and 5 minutes) and of 800°C – for the same time range – and equals more than 2g. The distinct loss, app. 1.5g, occurs after the following heat treatments: 500°C – 2880 minutes, 700°C – 10 and 30 minutes, 900°C – 2 minutes, 1000°C – 10 minutes. The smallest mass loss is found in the samples, which surface did not change, or only insignificantly changed, after the heat treatment. The smallest loss was observed in the sample heat treated at a temperature of 1000°C for 5 minutes.

The results of coating surface roughness before and after the abrasion are presented in Fig. 5-6.

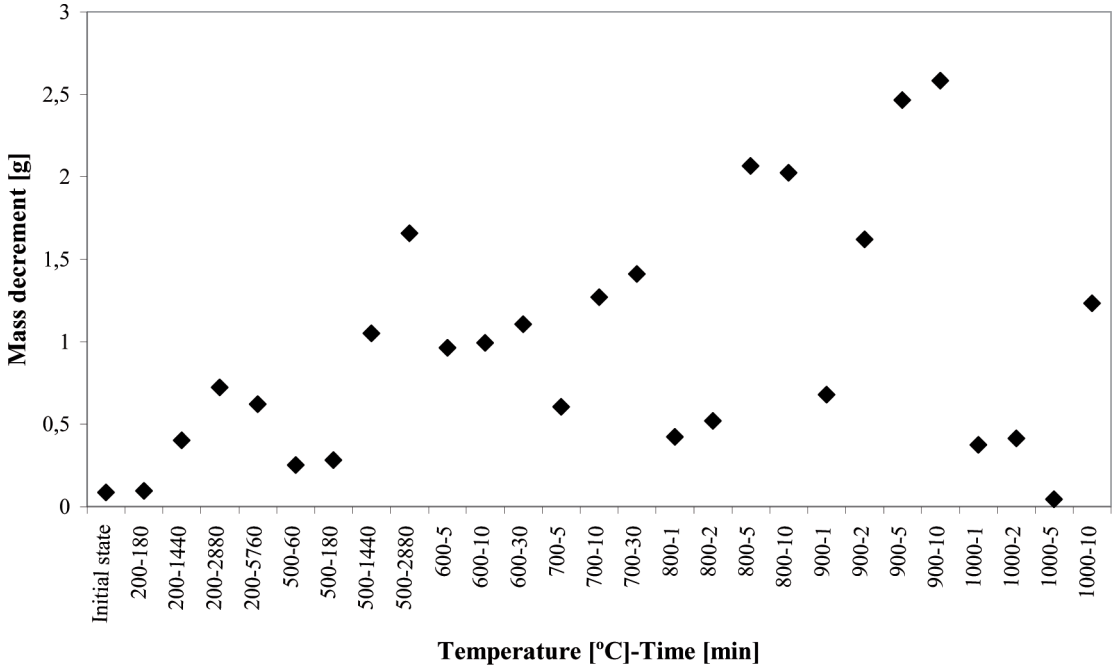


Fig. 4. The obtained results of the mass loss in dependence of the heat treatment conditions

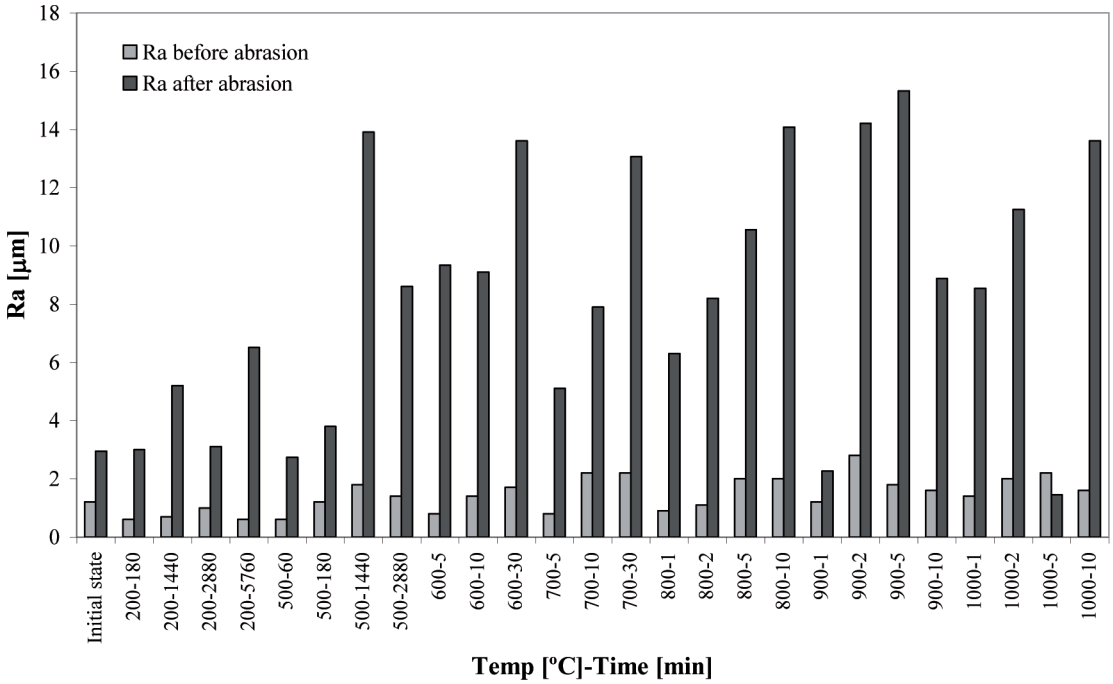


Fig. 5. Medium R_a values of coating surface roughness before and after the abrasion depending on heat treatment parameters

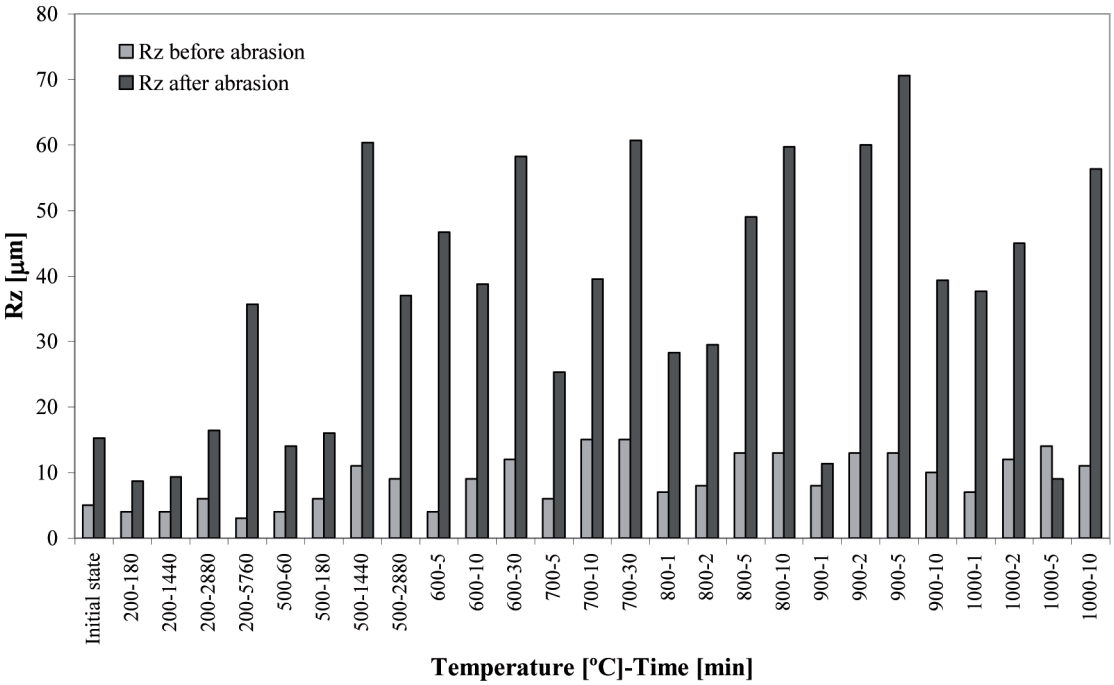


Fig. 6. Medium R_z values of coating surface roughness before and after the abrasion depending on heat treatment parameters

For the majority of samples after the heat treatment and abrasion the results indicate the increased roughness – from several dozen to a few hundred percent in relation with the after heating value - determined by R_a and R_z parameters. The highest R_a and R_z values are in the samples of the coating surface being completely dark and matt. The coating surface smoothing occurs in the samples, which underwent the heat treatment at 1000°C for 5 minutes.

3.2. Results of examinations of a force and depth of wearing out and a mass loss

Some examples of examination results of a force and depth of wearing out for samples after the heat treatment are presented in Fig. 7.

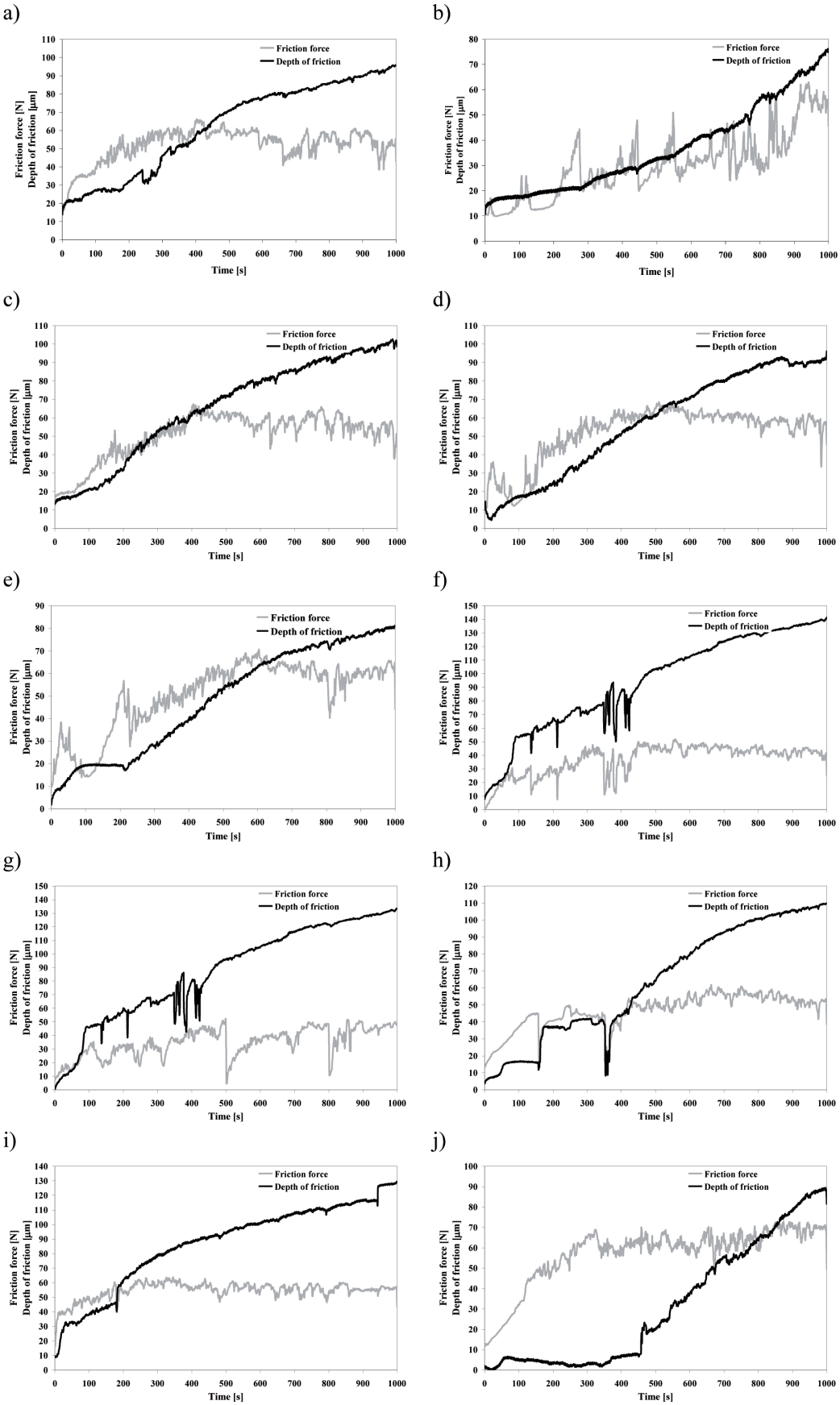


Fig. 7. Examination results of a force and depth of the coating wearing out – after the heat treatment
a) 500°C - 180min., b) 500°C - 1440min., c) 600°C - 5min., d) 600°C - 30min., e) 700°C - 5min., f) 800°C - 2min., g) 900°C - 1min., h) 900°C - 5min., i) 1000°C - 2min., j) 1000°C - 5min

The results of a force and depth of wearing out examinations indicate the diversified microhardness of the coating and base dependent on the heat treatment parameters. In the majority of cases the depth of wearing out curve is progressing, while the friction force is increasing until a certain moment and then stabilizes at the identical level.

For samples exposed at temperatures: of 500°C for 180 minutes (Fig. 7a), 500°C - 1440 minutes (Fig. 7b), 600°C - 5 minutes (Fig. 7c), 600°C - 30 minutes (Fig. 7d), after approximately 100-300 seconds of the test, the wearing out depth equals 20-30μm, it means that much as the average coating thickness after the heat treatment. The friction force for these cases increases to 30-60N. Further continuation of the test causes an increase of the wearing out depth to 80-130μm, while the friction force stabilizes at a level of 50-60N. The results indicate a uniform structure of the coating and base, without an occurrence of hard phases.

A slightly different character exhibit the wearing out depths of samples heat treated at 800°C - 2 minutes (Fig. 7f), 900°C - 1 minute (Fig. 7g) and 1000°C - 2 minutes (Fig. 7i). After app. 100 seconds of the test the wearing out depth equals app. 100μm, and the friction force 20-40N. This indicates that, regardless of a high temperature of the heat treatment, the coating is still soft. Thus, the time necessary for diffusive processes in the coating was too short. Further testing increases the wearing out depth to app. 130μm, while the friction force stabilizes after reaching app. 50N.

Characteristic abrupt change of the wearing out depth occurs for samples heat treated at: 700°C - 5 minutes, 900°C - 5 minutes and 1000°C - 5 minutes. After several dozen of seconds of the test duration the wearing out depth stabilizes at 15-20μm, while the friction force simultaneously increases to a level 45-50N (Fig. 7e, h). Then, after reaching a certain extreme friction force value, this depth abruptly increases to app. 40μm.

Exceptionally low value of the wearing out depth, being 3-6μm for app. 450 seconds of the test duration occurs for the sample heat treated at 1000°C - 5 minutes (Fig. 7j). The friction force increases during this time to 60-70N. Then the wearing out depth abruptly increases to app. 20μm and later on uniformly increases till the test end to a value of 90μm. A very long wearing out time, at preserving the minimum and stable in time depth, indicates the evolution of the coating structure due to diffusion processes – occurring during the heat treatment under these conditions – and the formation of the very hard, abrasion resistant phase. This idea is confirmed, among others, by the results of the percentage mass loss of samples undergoing the heat treatment after the tribological tests (by means of the T 05 tester) (Fig. 8).

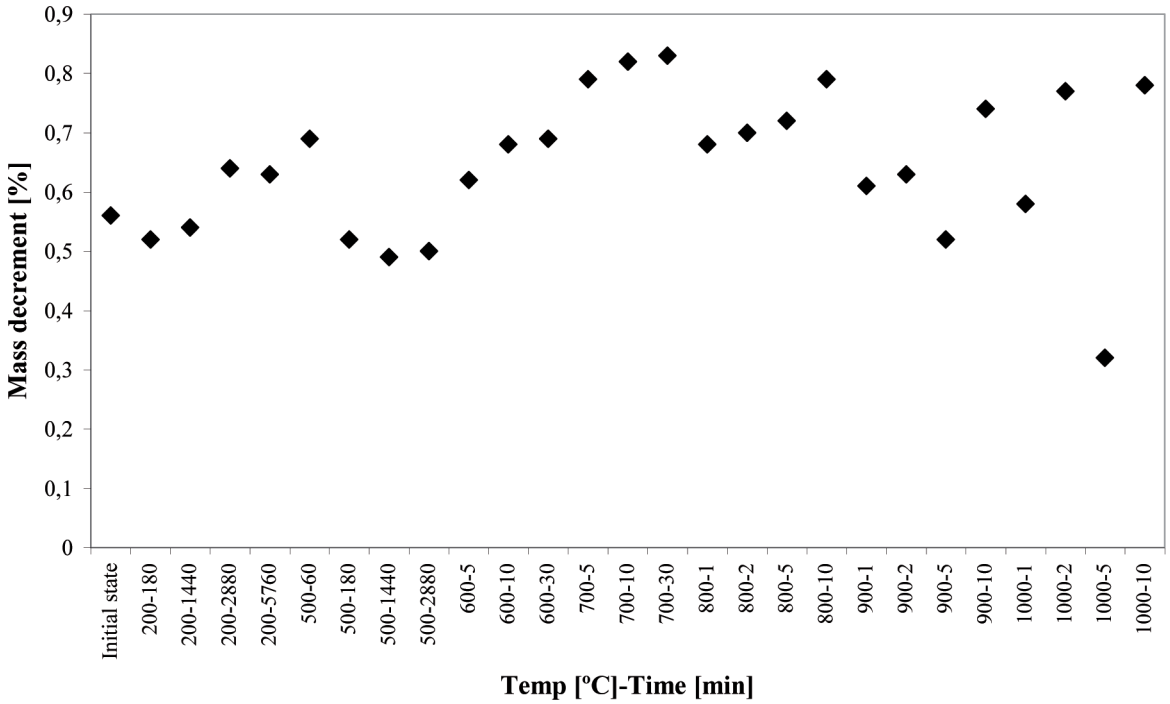


Fig. 8. Mass loss of samples – after the tribological tests – in dependence of the heat treatment parameters

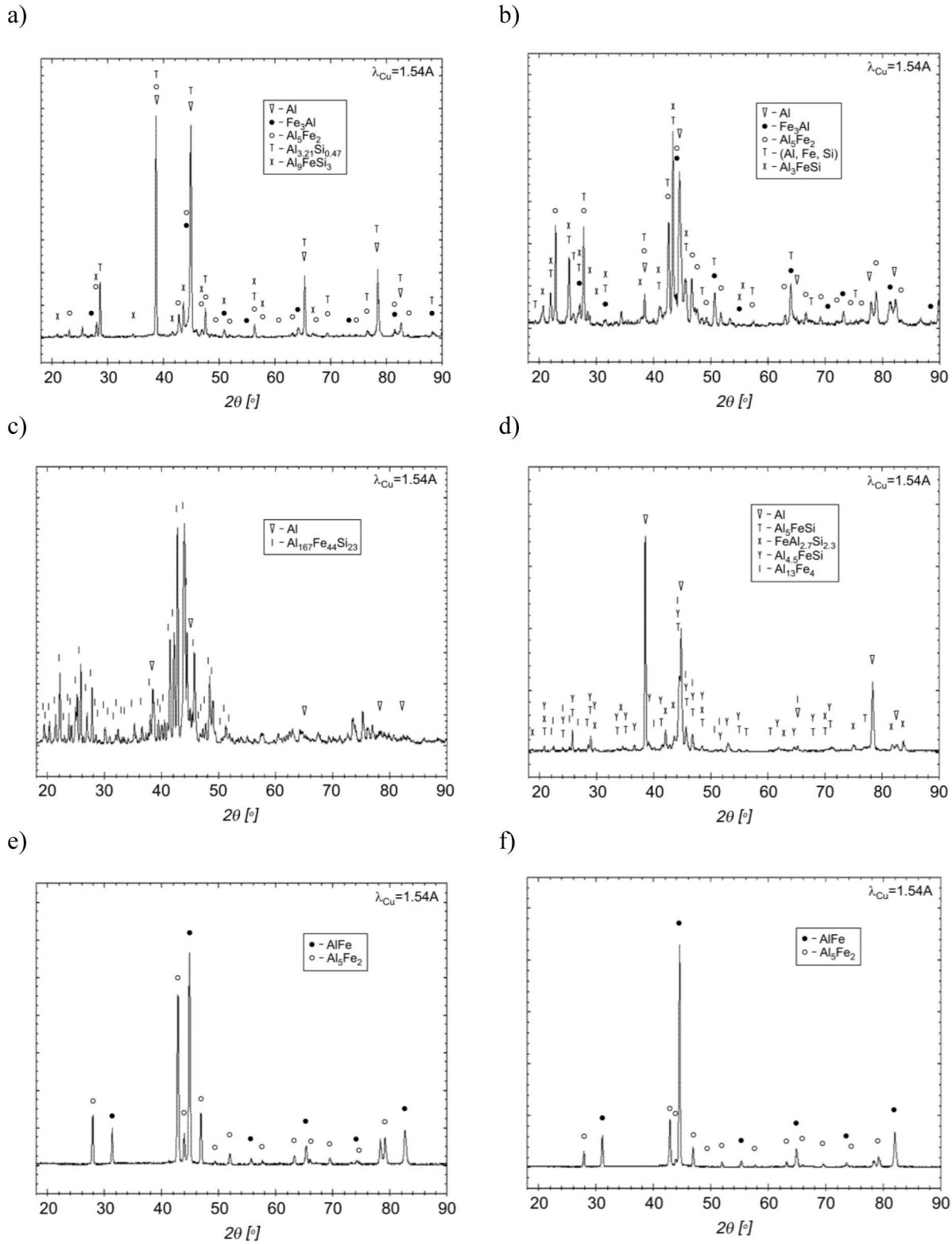


Fig. 9. Results of the X-ray phase analysis
a) 500°C - 1440min., b) 600°C - 30min., c) 700°C - 5min., d) 900°C - 1min., e) 950°C - 5min., f) 1000°C - 5min

For samples without the heat treatment and with the heat treatment which does not change the coating appearance, the mass loss – after the tribological test – equals 0.5-0.6%, (among others for samples heated at temperatures of 200 and 500°C). A partial change in the appearance, exhibiting itself as darker areas, causes a slightly larger mass loss being app. 0.6-0.7% (for samples after the heat treatment at 600°C - 10 and 30

minutes, 800°C - 1, 2 and 5 minutes, 900°C - 1 and 2 minutes, 1000°C - 1 minute). An increase of a temperature and time of the heat treatment, changing the coating surface from bright into dark and matt, causes in the majority of cases the mass loss increase by app. 0.8%, (among others for samples exposed to 700°C - 10 and 30 minutes, 800°C - 10 minutes, 900°C - 10 minutes and 1000°C - 2 and 10 minutes). However the smallest mass loss equal only app. 0.3% occurs for the sample heat treated at 1000°C for 5 minutes, regardless that the coating is completely dark. This result confirms structural changes occurring in the coating heat treated under these conditions, transforming the coating from soft and plastic into hard and abrasion resistant.

3.3. Results of the X-ray phase analysis

The results of the X-ray phase analysis for samples before and after the heat treatment are presented in Fig. 9.

These results indicate a fundamental influence of the heat treatment on structural changes occurring in the coating. The heat treatment at 500°C - 1440 minutes and 600°C - 30 minutes causes the formation of the multiphase coating structure, with a participation of pure Al phase as well as Al_5Fe_2 , $Al_{3.21}Si_{0.47}$, and Al_3FeSi phases (Fig. 9a, b). Phases, formed as the heat treatment result, and their intensity in the whole 2θ angle range, without a domination of whichever phase, indicate the uneven coating phase structure. The phase composition confirms the low hardness and thereby the low abrasion resistance. Similar situation occurs for samples heated at 700°C - 5 minutes and 900°C - 1 minute, but there the fraction of the Al and $Al_{167}Fe_{44}Si_{23}$ (Fig. 9c-d) and Al_5FeSi and $Al_{13}Fe_4$ phase is dominating. Definitely different is the situation for samples after the heat treatment at 950°C-5 minutes and 1000°C - 5 minutes. In these cases only two phases: Al-Fe and Al_5Fe_2 (Fig. 9e), or one AlFe phase (Fig. 9f) are dominating. The AlFe phase formed due to the heat treatments is characterized by a high hardness and abrasion resistance, which was confirmed by the results of the abrasibility, force and depth of wearing out and mass loss examinations.

4. Conclusions

The obtained results of abrasion resistance of aluminized steel strips are presented in the paper. Samples cut out from the DX52D + AS120 grade strips were heat treated at a temperature range 250-1000°C for 1-2880 minutes and then subjected to wear resistance examinations, by means of two different devices. On the basis of the performed investigations of the mass loss, roughness, friction depth and force, phase analysis and the analysis of the obtained results the following conclusions can be drawn.

1. Examinations confirmed the decisive influence of the heat treatment parameters on the state and properties changes of the Al-Si coating, manifesting themselves by the diversified abrasion resistance.

2. In the temperature-time range of the heat treatment, for which the coating is not changing its appearance and properties, mechanisms of grooving and microcutting are dominating and mutually competing in the wearing process.

3. The increase of the temperature and time of the heat treatment, which due to diffusion processes changes the coating appearance to dark and matt and into the single three component Al-Fe-Si layer, changes the wearing mechanism into the adhesive one.

4. Evolution of the state and properties of the coating under the influence of the heat treatment changing its appearance and structure, causes – apart from some exceptions – the worse abrasion resistance, revealing e.g. an increased mass loss.

5. However, there are some combinations of the heat treatment parameters, at which the coating becomes hard and at the same time exceptionally abrasion resistant, showing a minimum mass loss. The coating roughness under such conditions becomes smaller or only slightly larger in respect to its initial value.

6. The phase analysis documents the formation, due to certain heat treatments, of the Al-Fe phase, characterized by a high hardness and abrasion resistance, which is confirmed by the results of the abrasibility, force and depth of wearing out and the mass loss measurements.

Acknowledgements

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