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## SELECTED PROBLEMS OF ABRASION RESISTANCE OF ALUMINIZED STEEL TUBES

### WYBRANE PROBLEMY ODPORNOŚCI NA ŚCIERANIE ALUMINIOWYCH RUR STALOWYCH

The results of investigations, performed both under industrial and laboratory conditions, of the selected problems concerning the abrasion resistance of the aluminized steel strips and tubes are presented in the paper. Steel strips and tubes of the DX52D+AS120 grade with the Al-Si coating (of a silica content 9–12% and thickness ca 20  $\mu\text{m}$ ), hot dip on both sides were tested. The coating surfaces on the charge strip used for production of welded tubes were observed. Tests of thickness and roughness changes carried out on fragments of open-joint tube and on the finished product constituted the bases for laboratory investigations. An influence of various lubricating-cooling mediums on the abrasion resistance of the Al-Si coating was determined in laboratory tests. Investigations allowed to select the medium, which fulfils the expectations considering the coating surface quality in relation to its abrasion resistance. Devices for non-destructive coating thickness and roughness measurements were applied. The digital photo apparatus and optical microscope were used for illustrating coating changes due to abrasion tests.

*Keywords:* aluminized steel tube, coating, thickness, roughness, abrasion

W artykule przedstawiono wyniki badań zrealizowanych w warunkach przemysłowych i laboratoryjnych, obejmujących wybrane problemy odporności na ścieranie aluminiowanych taśm i rur stalowych. Badaniom poddano stalowe taśmy i rury z gatunku DX52D+AS120, z obustronnie nałożoną w sposób ogniowy powłoką Al-Si o zawartości krzemu ok.9-12% i grubości ca 20 $\mu\text{m}$  na każdej ze stron. Zrealizowano badania obserwacji powierzchni powłoki na taśmie wsadowej wykorzystywanej do produkcji rur zgrzewanych. Na fragmentach rury szczelinowej oraz gotowego wyrobu przeprowadzono badania zmian grubości i chropowatości powłoki, których wyniki stały się podstawą do realizacji badań laboratoryjnych. W badaniach laboratoryjnych określono wpływ zróżnicowanych środków smarująco-chłodzących na odporność na ścieranie powłoki Al-Si. Badania pozwoliły na wytypowanie środka spełniającego oczekiwania dotyczące jakości powierzchni powłoki w odniesieniu do jej odporności na ścieranie. W badaniach wykorzystano przyrządy do nieniszczących pomiarów grubości i chropowatości powłok. Do zobrazowania zmian powłoki po badaniach ścieralności wykorzystano mikroskop optyczny.

### 1. Introduction

Various steel grades after different heat and plastic treatment processes – depending on the responsibility of parts they are intended for - are used in an automotive industry. Among variety of parts, seamed steel tubes Al-Si coated, welded by high frequency currents, are used for exhaust systems elements. This material is widely applied since it combines strength and plastic properties of the base material with a high corrosion resistance of the silumin coating. A charge for the process of tubes production constitute steel strips of a thickness 0.3-3mm with hot dip Al-(8-11%)Si coating, app. 20-25 $\mu\text{m}$  thick on each strip side. The requirements concerning steel strips with the Al-Si coating are presented in [1-2]. The

Standard [3] determines steel grades which can be coated by aluminium layers. The requirements concerning plasticity, indispensable in tubes treatment processes and in anticorrosion protection, are decisive from the point of view of the product quality. The steel grade should be selected, especially on account of the need of further forming the aluminized products.

The technological production process of tubes from steel strips welded by high frequency currents consists of the following main unit processes:

- cutting of a wide strip into narrow bands, of a width depending on the diameter of the finished tube, allowances for flash as well as allowances resulting from the need of calibration,

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- strip perforating, if the produced tube is intended for a damper element,
- formation of an open-joint tube in a continuous system of rolling stands horizontal and perpendicular,
- welding by high frequency currents,
- removing of an external and internal fins,
- calibrating,
- cutting for the required dimensions.

Problems concerning production of seamed steel tubes were the subject of several investigations related to formation of open-joint tubes [4] and methods of their connection by means of welding and pressure welding processes and by a combination of these methods [5]. Studies related to the production and quality assessment of aluminized steel tubes intended for automotive industry were undertaken in several papers [6-10]. Separate investigations concerned the Al-Si coating [11-17].

One of the problems interfering with the production of aluminized seamed steel tubes is gluing the coating on tools in the section of rolls forming open-joint tubes and in the section of calibrating rolls (Fig. 1).



Fig. 1. Fragment of the surface of the forming roll with the glued Al-Si coating

Examinations of the coating indicate that in as-delivered condition it is rather soft and can be easily scratched (Fig. 2).

Microhardness of a coating is app.  $HV_{0.02} = 60-70$ , while of a base app.  $HV_{0.02} = 300$  [18]. This feature indicates the potential danger of a partial or local coating removal during the tube production process. This danger is more feasible since a strip and also tubes (open-joint and seamed) are nearly all the time in contact with various tools. From this point of view the most essential is the application of the proper lubrication-cooling medium separating strip and tube surfaces from forming tools.

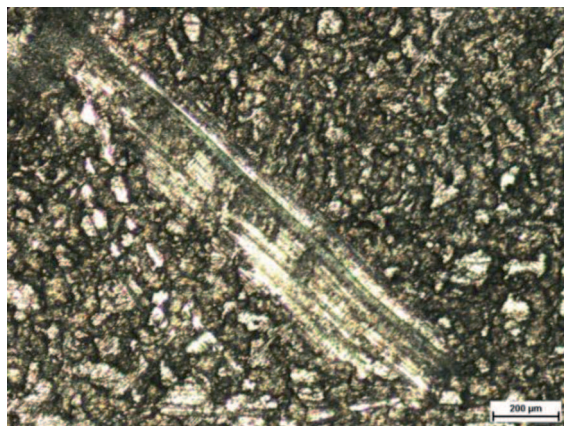


Fig. 2. Coating surface with scratching

Thus, it was decided to perform investigations under industrial conditions, based on the estimation of the coating thickness and roughness changes at various stages of the tube production. Dual-step simulation laboratory examinations, in which the steel tool was influencing the steel strip Al-Si coating under various frictions – reflecting the specificity of the tube production process – were also performed.

## 2. Experimental Technique

Steel strips of the grade DX52D+AS120 with the Al-10wt.%Si coating and tubes made out of them, intended for the exhaust systems, were applied as the experimental material. Its chemical composition is presented in Table 1. Examinations of the chemical composition were done by the optical emission spectroscopic method by means of the SPECTROLAB M7.

TABLE 1  
Metallic radii of rare earth metals and magnesium [12]

C	Mn	Si	P	S	Cr	Ni	Nb	Cu	Al	Fe
0.004	0.12	0.006	0.009	0.011	0.03	0.020	0.013	0.017	0.045	Bal.

In order to confirm the idea of an essential influence of tools on the Al-Si coating during the tube production process the experiments were performed under conditions resembling the industrial ones. Tests were done on a strip, on the formed open-joint tube and on the finished product. Thus, the process of the tube production was interrupted and the tube removed from individual rolling stands. The strip and open-joint tube are presented in Fig. 3, where measuring points on the external surface are marked.

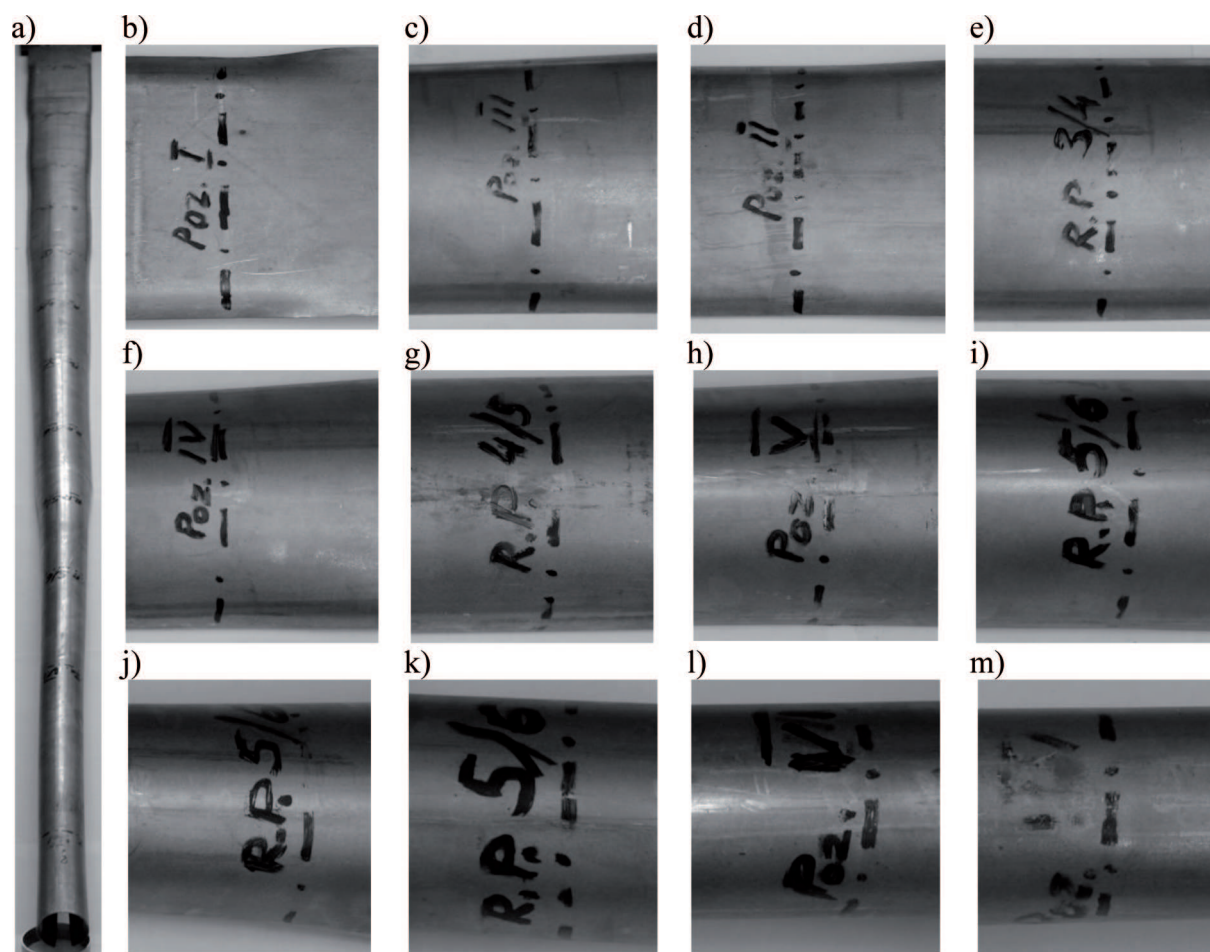


Fig. 3. Open-joint tube with marked measurement points

a) Open-joint tube, b) Directly from the strip accumulator, c) After passing through the I<sup>st</sup> rolling stand, d) After the II<sup>nd</sup> rolling stand, e) After the III<sup>rd</sup> rolling stand, f) After the III<sup>rd</sup> vertical rolling stand, g) After the IV<sup>th</sup> rolling stand, h) After the IV<sup>th</sup> vertical rolling stand, i) After the V<sup>th</sup> rolling stand, j) After the V<sup>th</sup> vertical rolling stand A, k) After the V<sup>th</sup> vertical rolling stand B, l) After the V<sup>th</sup> vertical rolling stand C, m) After the VI<sup>th</sup> rolling stand just before welding of the finished tube

Examinations of the coating thickness and roughness changes were performed on samples cut from tubes. The thickness measurements were done by the non-destructive method, by means of Elkometer 345. The thickness was measured on the external side of the tube in places of contact with forming and calibrating tools. 10 measurements were done in each selected tube zone. The average results are presented in a form of a diagram.

Measurements of the coating surface roughness were performed by the tracer method by means of the Form Talysurf apparatus with a photo-optical head of the Taylor Hobson Company. Two parameters,  $R_a$  and  $R_z$  determined in the Standard [19], were measured. The averaged numerical values of these parameters were obtained on the basis of 10 repetitions of measurements on the external tube side. The elementary segment  $l_e = 0.8\text{mm}$  and the measurement segment  $L_c = 4\text{mm}$  were applied. The averaged results are presented in a form of a diagram. The schematic presentation of the

coating with marked places where thickness and roughness was measured is presented in Fig. 4.

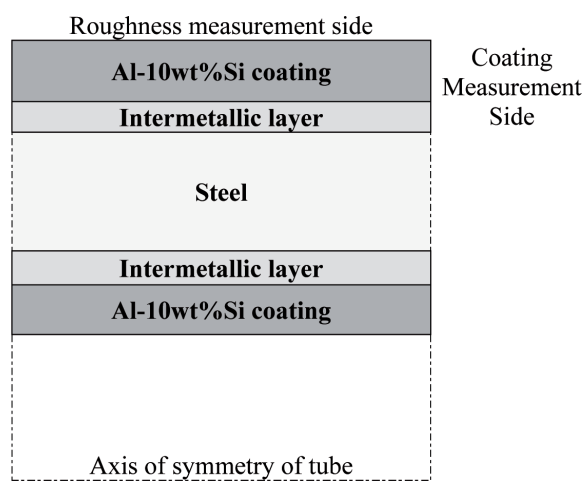


Fig. 4. Cross-section of the steel tube with the Al-Si coating. Places where the coating thickness and roughness was measured are marked A and B

On the grounds of investigations performed under industrial conditions, it was decided to measure the abrasion resistance under laboratory conditions. Investigations were realized in two stages. In the first stage the examinations of the friction wear of the aluminized steel strips under various lubrication conditions as well as of the friction coefficient were performed (Fig. 5).

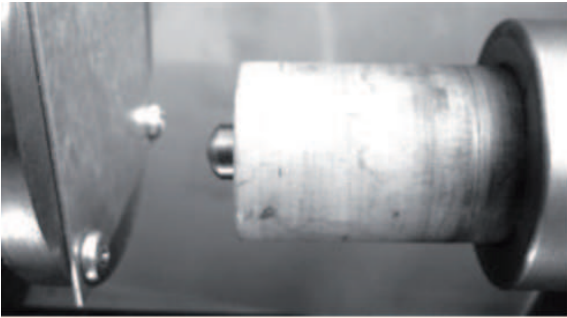


Fig. 5. Device for the abrasion resistance examinations

The aluminized steel sheets were used for wear tests performed by the block-on-ring wear tester (Fig. 6).

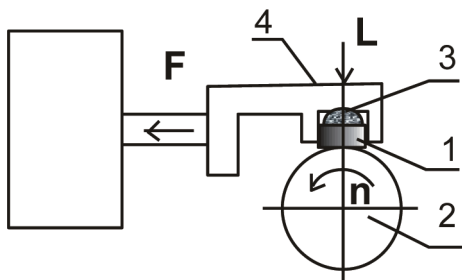


Fig. 6. Schematic view of block-on-ring tester

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  $\pm 1\%$ . The ring rotated with a constant rotating speed. The wear tests conditions chosen for the current investigations were:

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

The measured parameters were:

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

This tester enabled performing tests in accordance with the methods determined in Standards ASTM D 2714, D 3704, D 2981 and G 77. Tests were performed under conditions of a dry and a fluid friction with using the following cooling-separating mediums:

- water,
- Emulgol DS30 emulsion (of the Orlen Oil Company) and its 10, 20 and 30% water solutions,
- Emulgol ES12 emulsion (of the Orlen Oil Company) and its 10, 20 and 30% water solutions,

The friction investigations with using a lubricating medium were done in two ways, it means when the test started under a dry friction condition and when it started with the lubricating medium. The results are presented as graphs of the mass loss and coefficient of friction in dependence on the kind of the lubricating-cooling medium and the way of the test starting.

In the second stage the model investigations of the wear of the Al-Si coating being in contact with the tool steel (from which rolls forming tubes are made) with the application of the lubricating-cooling medium selected during the first stage of investigations – were carried on. Due to this the special stand for the abrasibility testing was designed and built. One part of the device constituted a round steel plate disk (20mm thick) of a diameter of 150mm mounted in jaws, with the possibility of performing the controlled angular motion. Four openings for fixing the samples were made on one plate surface. The second part of the device constituted the mandrel with a replaceable tip, mounted in a special sleeve (of a diameter 50mm and wall thickness 10mm) inside which the spring allowing for the application of a variable pressure load was placed.

The sample (of a diameter 180mm and thickness 1.5mm) was cut from the aluminized steel strip. The coating thickness on one side of the strip was app.  $24 \mu\text{m}$ . Four openings were made in the strip and it was fixed to the steel disk.

Tests, in each case, were performed with an identical – 200N – load of the mandrel on the coated sample and with the same rotational speed (30rot/min). Individual experiment was realized in 2 minutes. Lubricating-cooling mediums were continuously delivered into the contact zone.

As the lubricating-cooling medium the water solution of the Emulgol ES 12 emulsion of the Orlen Oil Company was applied. The experiment was performed under condition of a dry friction and with the application of the following lubricating-cooling mediums:

- water,
- 10% emulsion solution,
- 20% emulsion solution,
- 30% emulsion solution.

An influence of the lubricating medium on the coating on the strip was determined in an aspect of its wear and gluing to the mandrel. After each test the measurements of the coating thickness and roughness were made and microphotographs of the mandrel contact place with the coating were taken. Observation were made by means of the MULTIZOOM AZ 100 microscope of the Nikon Company.

### 3. Results and discussion

#### 3.1. Results of testing strips and tubes under industrial conditions

The results of macro- and micro-observations of the strip coating surface, intended for the tube production are presented in Fig. 7. The coating is characterized by

a smooth, bright and glossy surface without traces of peelings and unevenness.

The obtained results of the coating thickness, under industrial conditions are presented in Fig. 8, while the results of surface roughness measurements in Fig. 9.

The results indicate the characteristic decrease of the coating thickness: from  $29\mu\text{m}$  directly after leaving the strip accumulator, via app.  $25\mu\text{m}$  after passing through rolling stands, to  $22\mu\text{m}$  on the finished product. Taking into account the client's requirements, the coating thickness – in spite of its decrease by app. 20% – is satisfactory. However, assuming that such tendency will remain, it might occur that when charge strips with the coating thickness of  $20\text{--}23\mu\text{m}$  are applied the final thickness of the coating will be app.  $15\text{--}16\mu\text{m}$ , which is too small to meet the requirements concerning the tube corrosion resistance.

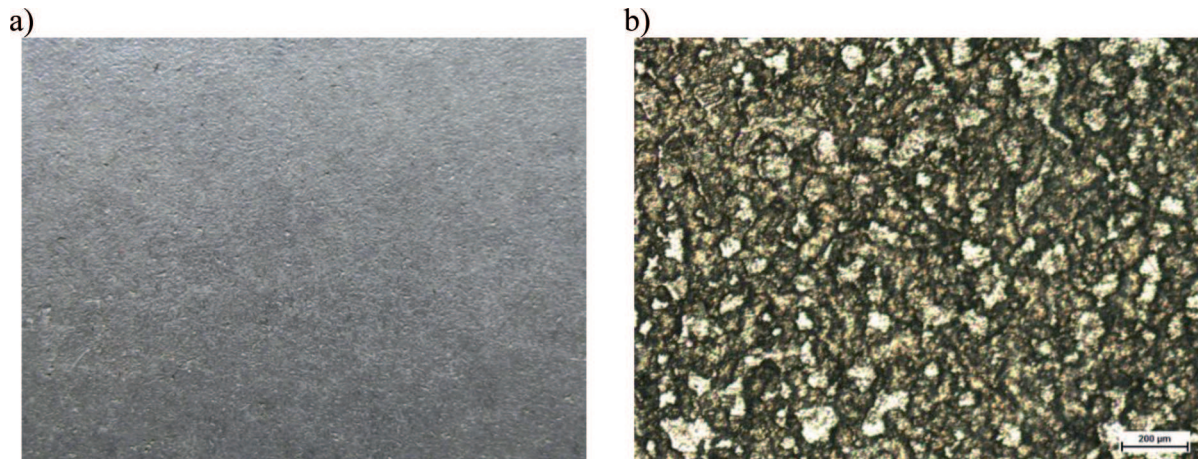


Fig. 7. Al-Si coating surface a) Macro-observation, b) Micro-observation

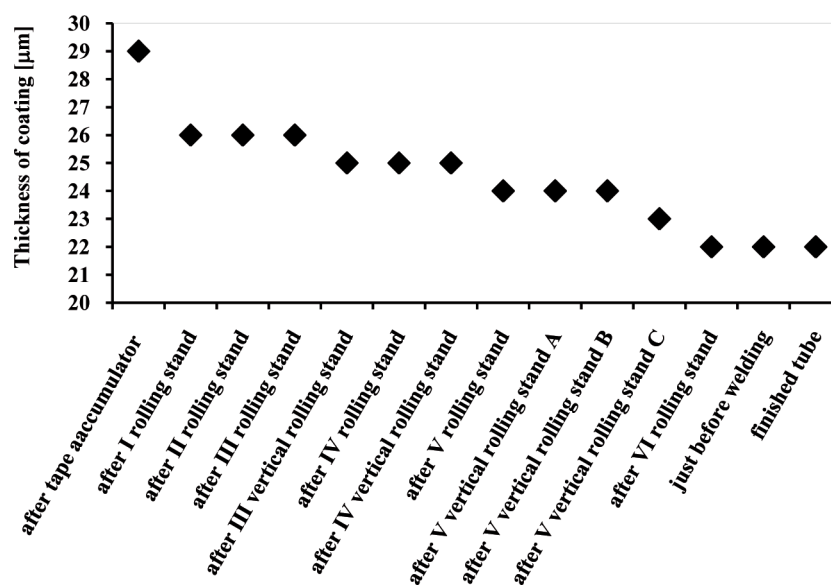


Fig. 8. Coating thickness at individual stages of forming

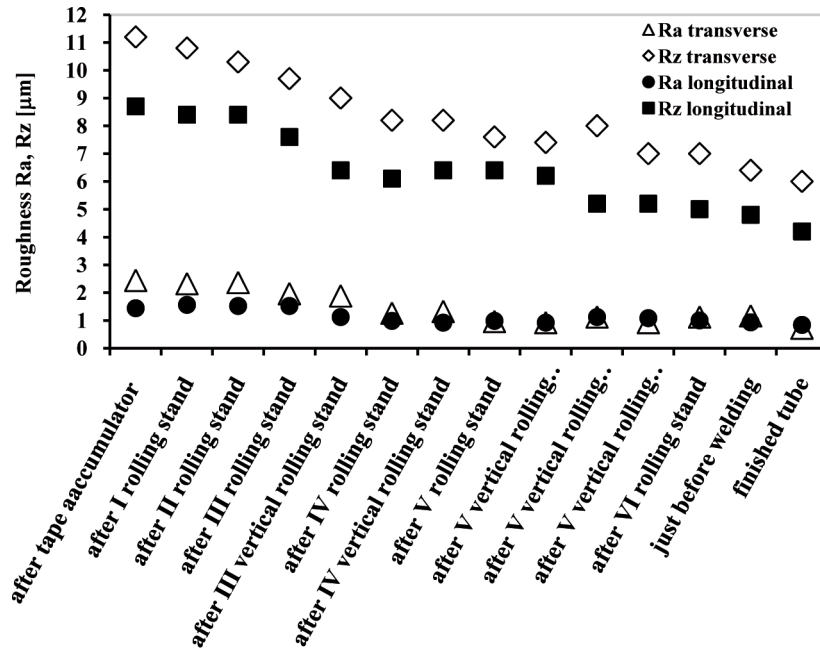


Fig. 9. Roughness parameters  $R_a$  and  $R_z$  at successive stages of forming

The roughness measurement results indicate lowering of the  $R_a$  parameter value, from  $R_a = 2\mu\text{m}$  after the strip accumulator, via app.  $R_a = 1.5\mu\text{m}$  after passing through rolling stands, to app.  $R_a = 1\mu\text{m}$  on the finished product. The roughness lowering, which indicates smoothing of the coating surface, is highly recommended since it minimizes the coating microporosity and decreases stresses at surface defects boundaries and due to this increases the material strength.

### 3.2. Results of the abrasive wear and friction coefficient measurements

The results of the abrasive wear tests performed by the block-on-ring wear tester are presented in Fig. 10-11, while the results of the friction coefficient measurements in Fig. 12-13.

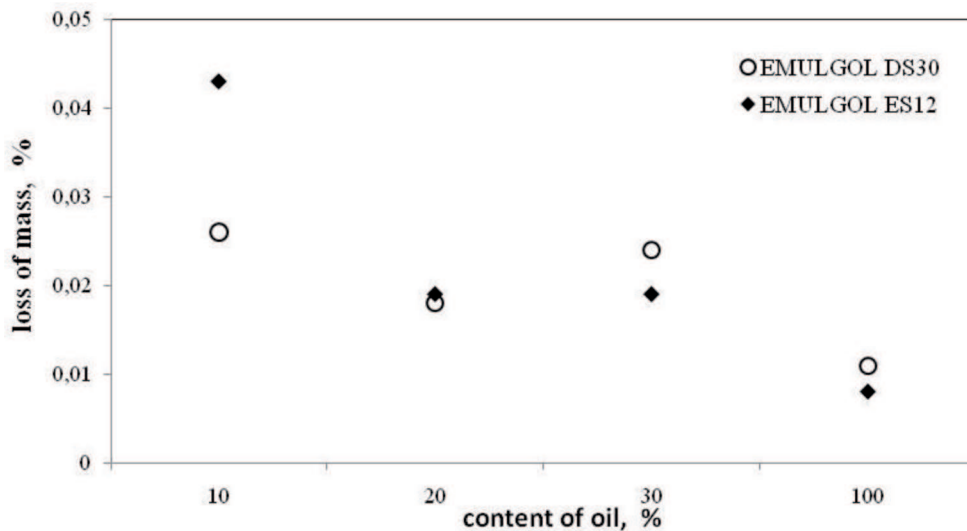


Fig. 10. Dependence of the emulsion content on the mass loss in the test, which started without a lubricant

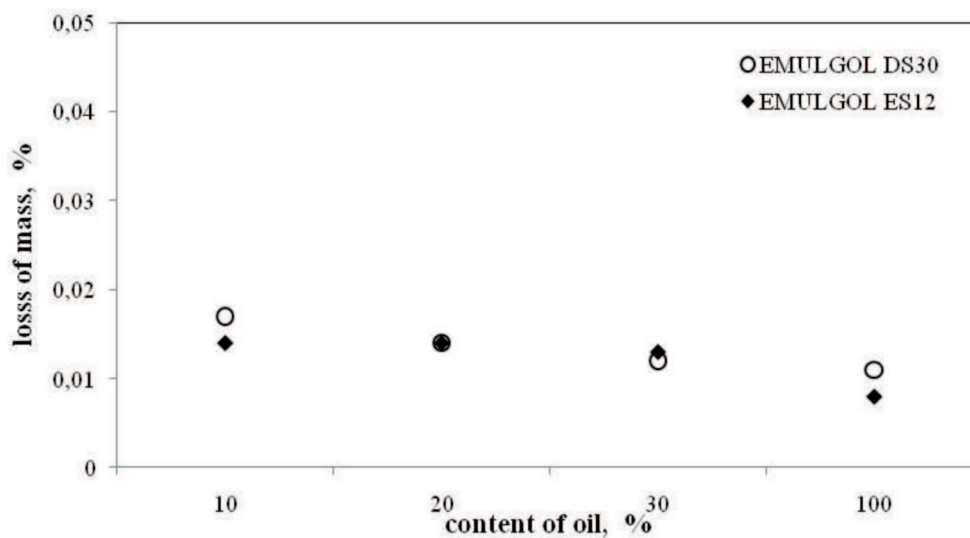


Fig. 11. Dependence of the emulsion content on the mass loss in the test, which started with a lubricant

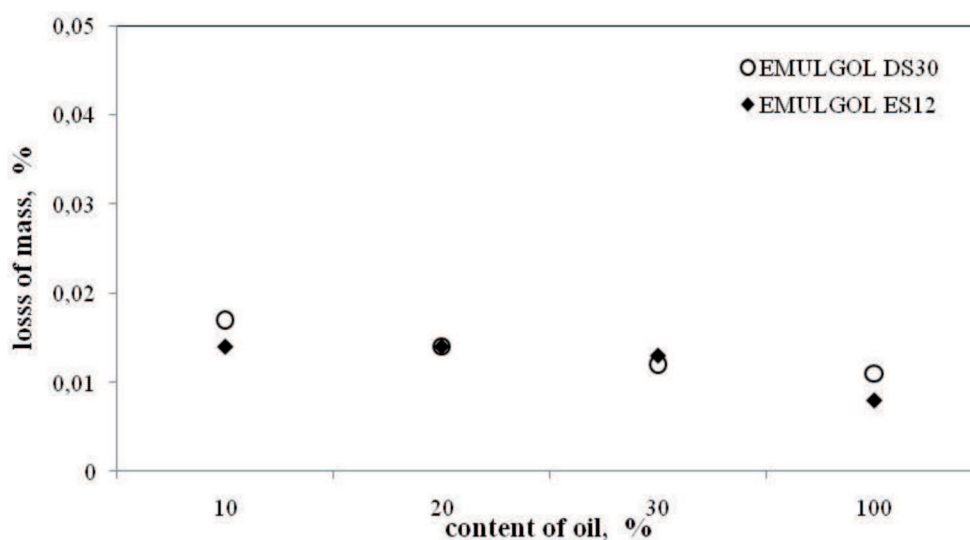


Fig. 12. Dependence of the emulsion content on the friction coefficient in the test, which started without a lubricant

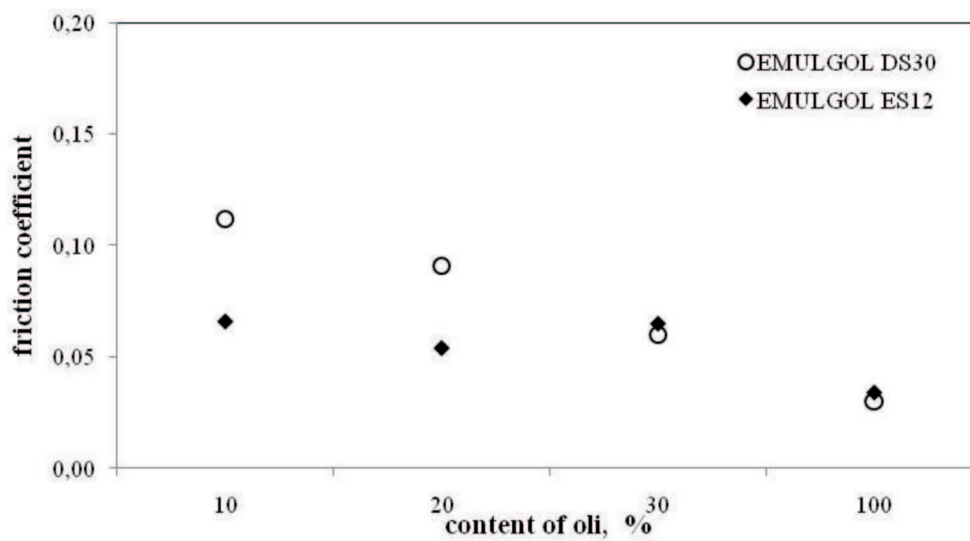


Fig. 13. Dependence of the emulsion content on the friction coefficient in the test, which started with a lubricant

The mass loss in a dry test equals 5.22%. An application of water as a lubricant and simultaneously as a cooling-separating medium causes a decrease of the mass loss to 0.56% as well as a decrease of the friction coefficient from 0.636 to 0.418. Addition of 10% of emulsion into water causes a very significant decrease of the mass loss (Fig. 10, 11) and nearly two-fold decrease of the friction coefficient (Fig. 12, 13). In the case of the water and emulsion mixture, in proportion 90 to 10, the way of starting of the friction test is very essential. When a lubricant is applied already at the test start the mass loss of the tested samples is twice smaller. A further increase of the emulsion content in relation to water does not cause essential changes neither in mass losses nor in friction coefficients. Out of all applied emulsions the best occurred the EMULGOL ES12. The performed tests indicated that an application of emulsion without a water addition was not necessary since the mass losses and friction coefficients were not significantly smaller than the ones obtained for emulsion-water mixtures.

Characteristic surface topographies after the wear test are presented in Fig. 14.

The friction surface obtained during the dry friction – presented in Fig. 13a – indicates that the dominating mechanisms of the friction wear was scratching, micro-cutting and adhesive wear. An application of water and emulsion-water mixture (Fig. 15b, c) completely eliminates the adhesive wear, which significantly decreases the friction coefficient.

**3.3. Results of abrasion resistance tests**

Abrasion resistance tests were performed by means of the specially built device, simulating the coating behaviour when it is in contact with tool steel being used for the tube forming and calibrating rolls. Water and 10, 20 and 30% water solutions of the EMULGOL ES12 emulsion – selected during the previous tests – were used as the lubricating-cooling medium. The results are presented as the coating thickness changes (Fig. 15), the coating surface roughness changes (Fig. 16) and the coating microscopic observations after abrasion (Fig. 17).

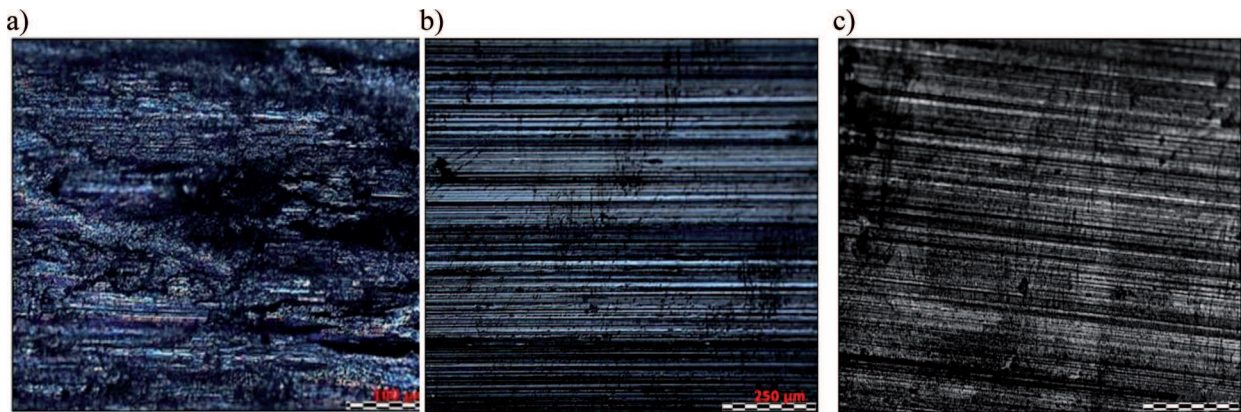


Fig. 14. The surface of samples after examining the wear resistance: a) without a lubricant, b) when applying water as a lubricant, c) when applying mixtures of water and 10% of the EMULGOL DS30 emulsion

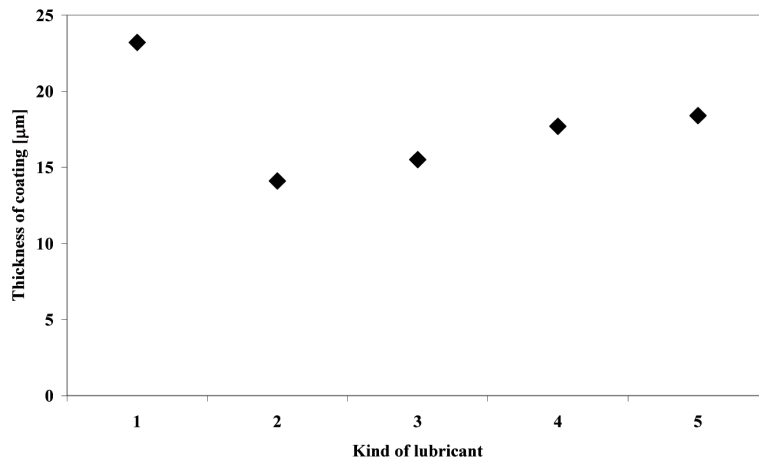


Fig. 15. Coating thickness after abrasion  
 1 – Initial state, 2 – Water, 3 – 10% water solution of ES12, 4 – 20% water solution of ES12, 5 – 30% water solution of ES12



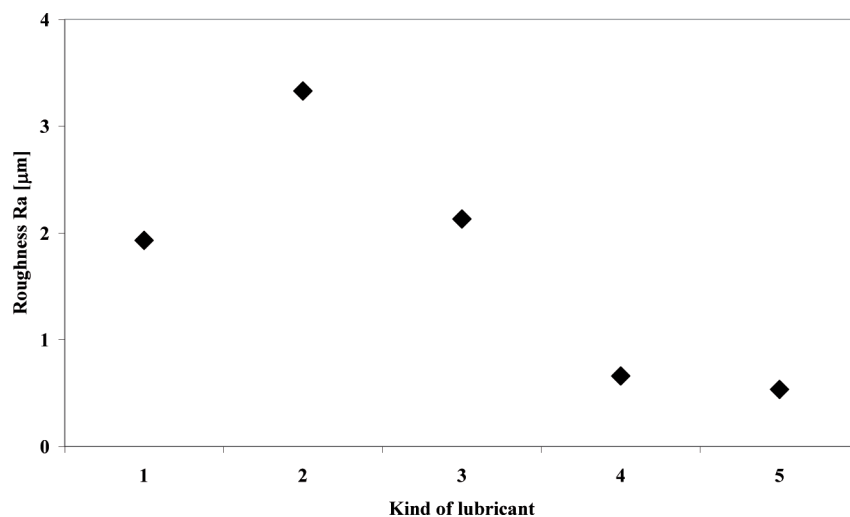


Fig. 16. Coating roughness after abrasion

1 – Initial state, 2 – Water, 3 – 10% water solution of ES12, 4 – 20% water solution of ES12, 5 – 30% water solution of ES12

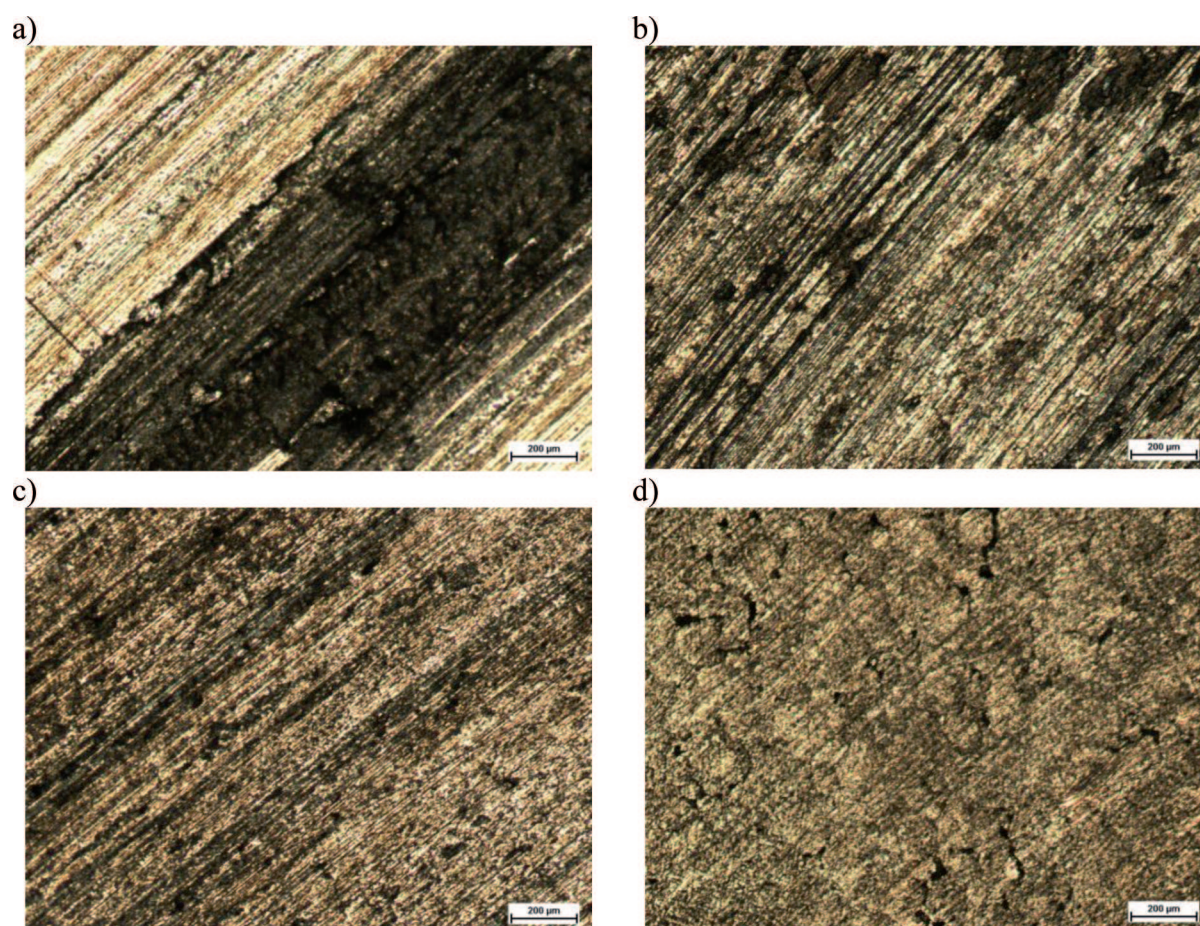


Fig. 17. The surface of samples after examining the wear resistance

a) with applying water as a lubricate, b) with applying mixtures of water and 10% EMULGOL ES12 oil, c) with applying mixtures of water and 20% EMULGOL ES12 oil, d) with applying mixtures of water and 30% EMULGOL ES12 oil

The coating thickness of samples used for abrasibility examinations was – on average –  $23\mu\text{m}$ . After abrasion, performed with water as a lubricating-cooling

medium, the coating thickness significantly decreased to app.  $14\mu\text{m}$ . An application of 10% water solution of the ES12 emulsion caused the coating thickness decrease to

app.  $15\mu\text{m}$ . The situation, after the abrasion performed with 20 and 30% water solution of the ES12 emulsion, was much better since the coating thickness decreased to  $17\mu\text{m}$  and  $18\mu\text{m}$  only – respectively.

The coating roughness in an initial state equals on average:  $R_a = 1.9\mu\text{m}$ . After abrasion performed with the use of water the roughness increased to a value  $R_a = 3.4\mu\text{m}$ . An application of 10% water solution of the ES12 emulsion caused the coating roughness increase to app.  $R_a = 2.1\mu\text{m}$ . A significant smoothness of the coating surface occurred after abrasion done with the use of 20% and 30% water solution of the ES12 emulsion and  $R_a$  equalled  $0.6\mu\text{m}$  and  $0.5\mu\text{m}$  – respectively. The attention should be drawn to the fact that the increased to 20 and 30% content of the ES12 emulsion in water caused the smallest decrease of the coating thickness and the biggest smoothing. Since at these both emulsion concentrations the coating's parameter values were similar, it should be recognised that 20% water solution of the ES12 emulsion had the best quality to price ratio and can be successfully applied as a lubricating-cooling medium at the production of the pressure welded tubes from aluminized steel strips.

The dominating mechanisms of the abrasive wear at the abrasibility testing was microcutting and adhesive wear. An application of water caused a high degree of adhesive wear and microcutting (Fig. 17a). The increased to 10 and 20% the ES12 emulsion content decreased the adhesive wear (Fig. 17b, c), while completely eliminated at the emulsion content being 30% (Fig. 17d).

#### 4. Summary

The obtained results of examinations, of the selected problems of the abrasion resistance of aluminized steel strips and tubes, performed both under industrial and laboratory conditions are presented in the paper. Basing on the analysis of the test results the following conclusions can be drawn:

1. Examinations confirmed the influence of forming and calibrating tools surfaces on the coating thickness and roughness changes of steel tubes intended for exhaust systems elements.
2. The Al-Si coating thickness measured on the charge strip and on the ready product differs by some micrometers, however its average value is within the limits recommended by the Standard; which is very essential on account of the coating corrosion resistance under exploitation conditions.
3. Maintaining the proper smoothness and cleanness of forming and calibrating tools on account of a danger of a coating thickness local change – which can cause the

corrosion resistance loss – is a substantial element of the process.

4. Measurements of the coating surface microgeometry indicates that the influence of rolls on the strip during the formation process is very essential, due to which the roughness parameter values are decreased (both under industrial and laboratory conditions).
5. The decrease of roughness parameter values is a warrant of the product quality increase in respect of aesthetics and techniques – the roughness decrease lowers stresses at surface defects boundaries thus improving a material strength.
6. Application of emulsion water solution – already at 10% emulsion content – significantly lowers mass losses and friction coefficients of the tested samples.
7. Slightly better results of the Al-Si coating abrasion resistance was obtained when the EMULGOL ES12 emulsion was used.
8. Application of a lubricating medium eliminates mechanism of adhesive wear in the investigated system.
9. Increased of the percentage content of the ES12 emulsion in water to levels of 20% and 30% causes the lowest decrease of the coating thickness and its best smoothing. Since at such emulsion concentrations the tested coating parameters values are similar it should be recognised that water solution of the ES12 emulsion has the best quality to price ratio and can be successfully applied as a lubricating-cooling medium at the production of the pressure welded tubes from aluminized steel strips.

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