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THE ABRASION OF AL-SI COATINGS WITH DIFFERENT SILICON CRYSTAL MORPHOLOGY, APPLIED IN AUTOMOTIVE SILENCERS

ŚCIERALNOŚĆ POWŁOK Al-Si O RÓŻNEJ MORFOLOGII KRYSZTAŁÓW KRZEMU STOSOWANYCH W TŁUMIKACH SAMOCHODOWYCH

Key words:

abrasibility, Al-Si coatings, hot dip, cold clad plated coatings, exhaust systems

Słowa kluczowe:

ścieralność, powłoki Al-Si, powłoki ogniowe, powłoki platerowane, samochodowe układy wydechowe

Abstract

This paper compares the abrasibility of aluminium-silicon coatings with silicon crystals of various forms. The tests were performed on Al-Si coatings with the chemical comp67890-osition corresponding to that of hypoeutectic and peritectic silumins (6-10wt% Si), manufactured by hot-dipping on type X2CrTi12 steel and by cold cladding with 60% cold reduction on AlMn1Cu

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alloy. The hot-dip coatings deposited on X2CrTi12 steel were investigated as made and after a two-stage heat treatment: 420°C/2h/water and 120°C/2h/air.

The morphology, shape, and size of silicon crystals in the coatings were studied under a microscope and with the image analysis technique (determining the shape factor among other parameters). Image analysis was also applied to the evaluation of abrasive wear resistance of the coatings using a ball wear test. Their adhesion strength was tested with the scratch test method.

The test results indicated that the change in Al-Si coating silicon crystal morphology (from large sharp edged and needle-like to smaller rounded particles) was heat induced, which, compared to the pre-treatment condition, lowered abrasion resistance values and produced a more uniform abrasion loss. This condition was regarded as more desirable in terms of maintaining the coating continuity during drawing, with no risk of spalling. It was also demonstrated that clad Al-Si coatings could provide an alternative solution for the widely used hot dip coatings on steel sheet.

INTRODUCTION

The automotive industry uses deep drawing to produce steel parts of exhaust systems. A key issue of this technology is the material resistance to abrasion. Various factors affect tribological properties of materials. These include density, microstructure, particle size, and residual stresses. Tribological properties are important at the production stage and during the vehicle exploitation when the parts are exposed to mechanical abuse and condensate. To provide long-term aesthetic results and protection against corrosion, the components are typically made of the materials with pre-deposited metallic coatings [**L. 1–6**]. From a technological standpoint, the production of components of coated sheet is more economical. A relatively low price of hot-dip Al-Si coated sheet makes it a popular material for automotive exhaust system components. Depending on the silicon content and cooling rate/conditions, the coating structures can be made up at various proportions from a mixture of solid solution particles, silicon crystals, aluminium-silicon eutectic, and precipitations of intermetallic compound phases. The aluminium matrix of coatings is easy to form and abrade, whereas hard silicon crystals promote lower friction and wear during forming. Crystallizing silicon in the liquid phase has a coarse plate-like morphology. Since the silicon crystals are brittle, they may spall and cause discontinuity of the coating. Therefore, it seems reasonable to consider a modification of the silicon crystal morphology in hot-dip coatings, which are introduced prior to drawing, or to use a different coating technology [**L. 1, 2, 7**].

This paper proposes a method for the modification of silicon crystals in hot-dip coatings on steel through heat treatment and an evaluation of Al-Si coatings on aluminium sheets produced through cladding with thixocast alloy when silicon crystals are nearly spherical. Production of exhaust systems from such clad sheets would provide an additional asset – vehicle weight reduction – currently being one of the key requirements faced by the automotive industry focused on the reduction in fuel consumption and harmful emissions. Today, plated aluminium sheets are used to manufacture heat exchangers, collectors, and other parts **[L. 8–12]**.

MATERIALS AND METHODS

The tests were carried out on commercial Al-Si coated sheets made with hot-dip methods and by cladding. Chemistries of the coatings corresponded to hypo and peritectic silumins (6-10wt% Si). The coatings were investigated in an as-received condition and after a two-stage heat treatment involving solution treatment from 420°C and ageing treatment at 120°C (**Table 1**).

Table 1. Type of coatings under tests
Tabela 1. Rodzaje badanych powłok

Al-Si coating	Chemical composition (EDX),%	Thickness, μm	Substrate
Hot-dip	Si-6.5 Fe-0.4 Al – rest	14	X2CrTi12
Heat treated hot-dip (420°C/2h/water + 120°C/2h/air)		14	
Cladding (cold, cold reduction 60%)	Si-9.6 Al – rest	90	AlMn1Cu

The tests involved the following:

- Evaluating cross-sectional microstructures of the coatings (Axiovert 25 ZEISS light microscope) and analysing the size, volume fraction, and shape factor of Si crystals with the use of Image ProPlus for Windows software on the images recorded at 500x magnification (real width 140 μm);
- Evaluating abrasive wear resistance coatings in a ball wear test that used a thermally improved 4 mm diameter steel ball supported at three points (two on the roller and one on the surface of the specimen being tested; and,

Eight different test times were selected experimentally: 1, 2, 3, 4, 5, 10, 15, and 30 minutes at a constant speed of rotation of 6 rev/s and a 30° inclination of the stage relative to the base of the test table (**Fig. 1**) [**L. 13]**. Surface areas and diameters of the wear sections were measured using Image ProPlus for Windows software.

- Evaluating cohesion-adhesion strength of the coatings with the use of a scratch tester manufactured by Revetest Xpress CSM Instruments.

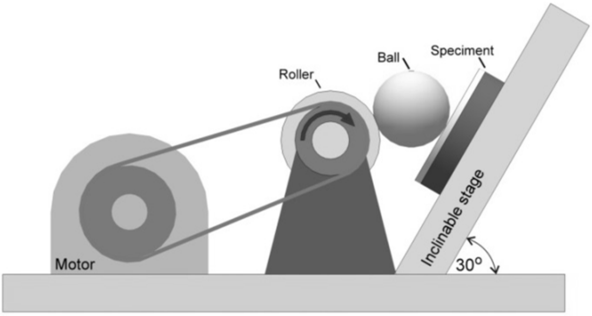

Fig. 1. Schematic diagram of a ball wear test
Rys. 1. Schemat pomiaru kulotesterem

The depths of indentation made in the coatings with a Vickers indenter along the sheet rolling direction were measured and recorded electronically. The load from the Vickers indenter was increased from 1N (initial load) to 10N on the 5mm length of the scratch.

RESULTS AND DISCUSSION

Microstructure of coatings

The as-received hot-dip coating microstructure was composed of the α_{Al} – solid solution and the eutectic with Si crystals. A layer of intermetallic phases Fe-Al/Fe-Al-Si at the near substrate zone formed as a result of aluminium diffusion into the steel substrate. In the plane parallel to the sheet surface (**Fig. 2a**), the eutectic Si crystals had a plate-like form characteristic of cast alloys. Cross-sectional observations revealed that the large plates of silicon were often arranged in the direction of the coating growth, that is, nearly perpendicular to the substrate. In extreme cases, the silicon plates had a size equal to the coating thickness (**Fig. 2b**).

Heat treatment changed the microstructure of the coatings, which resulted in the reduced size of the Si crystals and the evident rounding of their shapes and edges (**Fig. 2c**). The heat treatment parameters did not cause any changes in the thickness of intermetallic phase layer.

The clad coating had a composite type structure where: regular polyhedral silicone crystals were uniformly arranged in the aluminium matrix (**Fig. 3**) **[L. 1]**.

Results from the image analysis of Si crystal shape and volume fraction in the microstructure are summarized in **Table 2**. The results confirmed the findings from microscopic examinations. The most regular polyhedral shape (shape factor ~ 1) was observed in the Si crystals of the clad coatings. Silicon in the heat-treated hot-dip coating had a similar value to the shape factor: 1.33. In addition, after the heat treatment, the void fraction decreased, which means that the crystals underwent substantial dispersion, and it was no longer possible to observe the smallest particles at the 500x magnification.

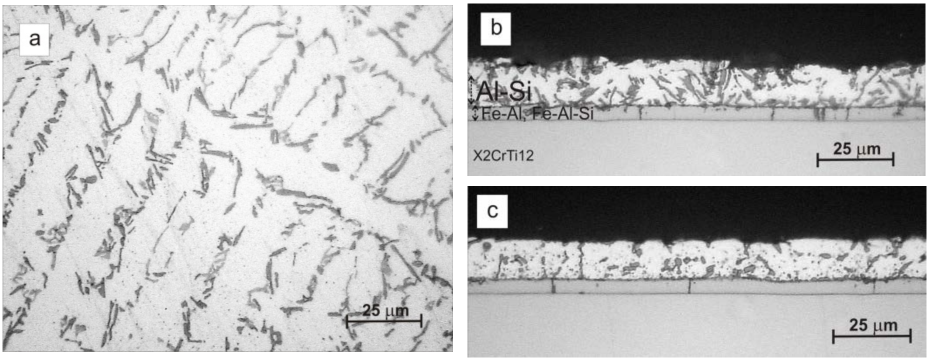

Fig. 2. Microstructure of Al-Si hot-dip coating: a) initial condition in a plane parallel to the sheet surface, b) initial condition, cross-section, and c) condition after heat treatment, cross-section, 1% HF etching

Rys. 2. Mikrostruktury powłoki ogniowej Al-Si: a) stan wyjściowy w płaszczyźnie równoległej do powierzchni blachy, b) stan wyjściowy na przekroju poprzecznym, c) po procesie obróbki cieplnej na przekroju poprzecznym, traw. 1%HF

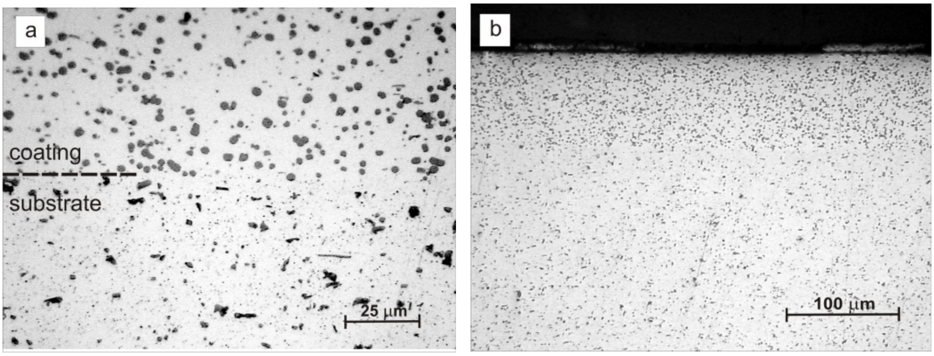

Fig. 3. Cross-sectional microstructure of Al-Si cold-clad coating, (a) 500x magnification, and (b) 100x magnification, 1% HF etching

Rys. 3. Mikrostruktura powłoki platerowanej Al-Si na przekroju poprzecznym, a) pow. 500x, b) pow. 100x, traw. 1%HF

Table 2. Results of analysis of the shape and volume fraction of Si crystals

Tabela 2. Wyniki analizy kształtu i udziału krystalitów Si

Coating	Analysis area, μm^2	Diameter max., µm	Diameter min., µm	Mean diameter µm	Shape factor*	Volume fraction %
Hot-dip	2.97	3.02	1.04	2.03	1.66	8.98
Heat treated hot-dip	2.97	2.67	1.09	1.88	1.33	8.16
Cold clad	3.52	1.97	1.45	1.72	1.05	14.00

* value of 1 represents the shape of a sphere

RESISTANCE TO ABRASIVE WEAR

The development of abrasive wear test results involved microscopic evaluation of the wear regions (spherical cavities) (**Fig. 4**) in the coatings and computer analysis of these cavities (**Fig. 5**). It was demonstrated that the smallest cavities occurred in the hot-dip coating in the initial condition. At the same time, the cavities had the most irregular edges as a result of Si crystal spalling. These crystals became an additional abrasive medium causing the gouging of the coating matrix. Stronger abrasion was observed in heat-treated coatings as compared to their initial condition. The clad coatings abraded to the intermediate extent relative to the hot-dip coatings.

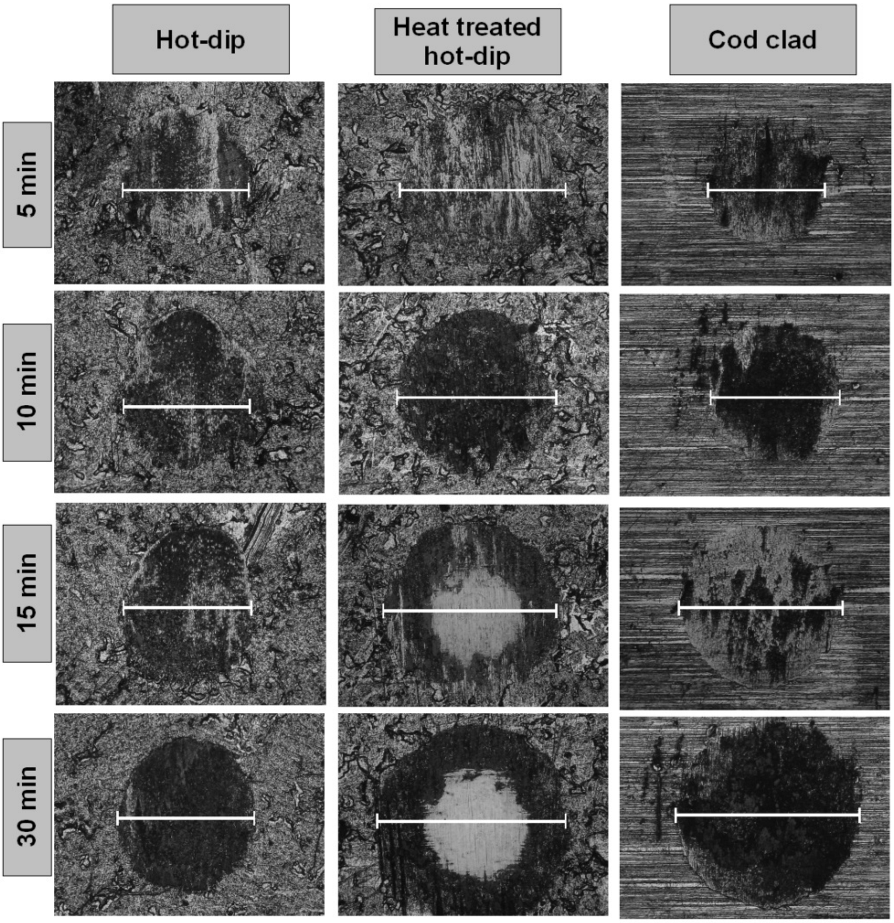

Fig. 4. Wear regions (spherical cavities) in coatings after the *abrasion test* (length indicates average diameter used to calculate the wear surface area)

Rys. 4. Wytarcia w powłokach po teście ścieralności (odcinki wskazują średnie średnice użyte do obliczenia pól wytarć)

In terms of the abrasion kinetics, the highest rate of wear was observed during the first five minutes of the test, and then the rate slowed down **(Fig. 5)**.

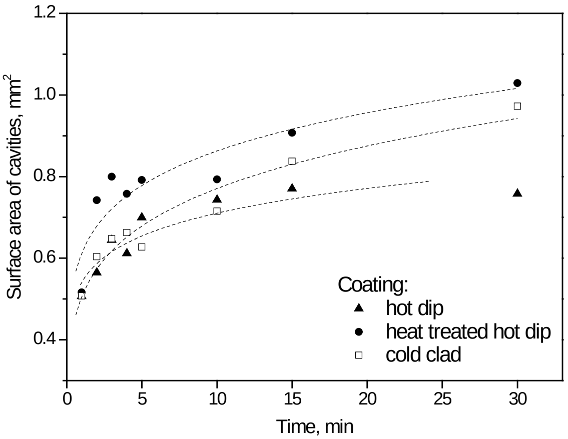

Fig. 5. Surface area of *cavities* in coatings after various *abrasion test* times
Rys. 5. Pola powierzchni wytarć w powłokach po różnym czasie testu ścieralności

ADHESION WEAR – SCRATCH TEST

The results of scratch test are shown in the form of diagrams of friction coefficient μ and penetration depth (Pd) variations under load increasing to 10N and in the residual depth, unloaded (Rd) **(Fig. 6)**.

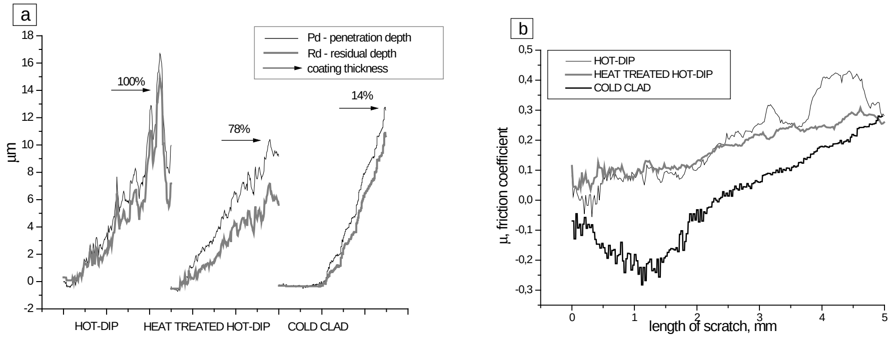

Fig. 6. Scratch test (a) penetration depth, Pd and Rd along 5 mm length of scratch, and (b) friction coefficient μ
Rys. 6. Test zarysowania powłok a) głębokości Pd i Rd na długości rysy: 5 mm, b) współczynnik tarcia μ

The scratch depths varied with the coating type. The deepest scratch, deeper than the thickness of the aluminium coating, was observed in the hot-dip coatings, where: it included the layer of intermetallic phases. The scratch depth of the heat-treated coating was the smallest and covered about 78% of its thickness. The refinement of crystals was reflected in a more uniform growth of the scratch depth and an increased friction coefficient along the scratch length. Friction coefficients were increasing with the crack length and penetration depth. The smallest coefficient was observed in the clad coating, where: its increase was the most uniform in time. This coating had a smooth surface (and oxide layer) compared with the hot-dip coating surfaces. Therefore, at the beginning of the test within a 2 mm section, the penetrator slid over the surface until the load threshold of about 3.5 N. The friction coefficient of this coating increased faster, because the scratch deepened faster, until its values matched those for hot-dip coatings, i.e. about 0.28. All coatings maintained adhesion in the scratch test [**L. 1, 14**].

CONCLUSIONS

Abrasive wear resistance of AlSi6 alloy coatings used in the production of exhaust systems depends on their microstructure, which is in turn dependent on the coating technology applied. The hot-dip coating with a microstructure containing plate-like eutectic silicon crystals showed the highest wear resistance. It was demonstrated that the coating abrades non-uniformly because of the spalling of silicon crystals.

A two-stage heat treatment is able to change the morphology of the silicon crystals and facilitate the formation of smaller crystals with rounded edges. The heat-treated coating demonstrated lower resistance to abrasive wear at more uniform abrasion and lower risk of crystal spalling. This indicates that certain lowering of overall abrasion resistance can be compensated with improved protection provided by coating continuity.

It was also demonstrated that AlSi6 plated aluminium alloy sheet can be an alternative option to hot-dip AlSi6 steel sheet in the production of exhaust systems. A slightly lower resistance to abrasive wear of these cold clad coatings is compensated by their smooth surface and lower friction coefficient μ.

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Streszczenie

W pracy dokonano porównania ścieralności powłok aluminiowo-krzemowych o zróżnicowanej formie kryształów krzemu. Badano powłoki Al-Si, o składzie chemicznym odpowiadającym gatunkom siluminów pod- i okołoeutektycznych (6–10% Si) wykonane metodą ogniową na stali X2CrTi12 oraz poprzez platerowanie na zimno z 60% stopniem zgniotu na stopie AlMn1Cu. Powłoki ogniowe na stali X2CrTi12 badano w stanie po otrzymaniu oraz po dwuetapowej obróbce cieplnej: 420°C/2h/woda i 120°C/2h/powietrze.

W pracy dokonano oceny morfologii, kształtu i rozmiarów kryształów krzemu w powłokach metodą mikroskopową z użyciem komputerowej ana-

lizy obrazu (wyznaczając m.in. współczynnik kształtu). Analizę obrazu zastosowano również do oceny odporności na zużycie ścierne powłok przeprowadzonej kulotesterem. Dodatkowo badano ich adhezję metodą zarysowania.

W wyniku badań stwierdzono, że zmiana morfologii kryształów krzemu w powłokach Al-Si spowodowana obróbką cieplną (z dużych ostrokrawędziowych i iglastych na mniejsze i o wyoblonych kształtach) spowodowała obniżenie ich odporności na ścieranie w stosunku do stanu przed obróbką, przy jednoczesnym bardziej równomiernym ścieraniu się powłok. Stan taki uznano za korzystniejszy z punktu widzenia zachowania ciągłości powłok podczas tłoczenia, bez ryzyka powstawania wykruszeń. Wykazano ponadto, że powłoki platerowane stopem Al-Si mogą stanowić alternatywę dla produkcji detali układów wydechowych w miejsce obecnie stosowanych powłok ogniowych na blachach ze stali.