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INFLUENCE OF CORROSION PROCESSES ON FRICTION AND WEAR OF TIN COATINGS OF WIRE CONNECTORS

WPŁYW PROCESÓW KOROZYJNYCH NA TARCIE I ZUŻYWANIE POWŁOK CYNOWYCH NA KOŃCÓWKACH KONEKTOROWYCH PRZEWODÓW ELEKTRYCZNYCH

Key words: connectors, corrosion, tin coatings, electrical connectors.

Abstract: The paper describes the results of metallographic, tribological, and microscopic tests of wire connectors. It was shown that the structure and thickness of the tin layer on the copper element varies greatly. The paper describes the results of tribological investigations for electrical connectors in the initial state and covered with a layer of oxides formed as a result of corrosion. The results of tribological tests have shown a great influence of the oxide layer on friction and wear of tin coatings. The results of friction factor measurements were confirmed by microscopic observations. The tests confirmed that the oxide layer reduces plastic deformation of the tin coating and limits its tribological wear. Due to the brittleness and low adhesion of the oxide layer, friction-induced chipping was observed.

Słowa kluczowe: konektory, korozja, powłoki cynowe, złączki elektryczne.

Strerszczenie: W pracy opisano wyniki badań metalograficznych, tribologicznych i mikroskopowych końcówek wiązek elektrycznych, tzw. końcówek konektorowych. Wykazano duże zróżnicowanie struktury i grubości warstwy cynowej na elemencie wykonanym z miedzi. W pracy opisano wyniki badań tribologicznych dla końcówek konektorowych w stanie wyjściowym i pokrytych warstwą tlenków powstałych na skutek korozji. Wyniki badań tribologicznych wykazały duży wpływ warstwy oksydacyjnej na proces tarcia i zużywanie powłok cynowych. Wyniki pomiarów współczynnika tarcia potwierdzono obserwacjami mikroskopowymi. Wykazano, że warstwa tlenków zmniejsza deformację plastyczną powłoki cynowej i ogranicza jej zużywanie tribologiczne. Ze względu na kruchy charakter i małą przyczepność warstwy tlenkowej zaobserwowano wykruszanie się jej spowodowane tarciem.

INTRODUCTION

The electrical wiring of motor vehicles has been used only to ensure the ignition of the mixture in the engine cylinders **[L. 1, 2]**. Nowadays, the electrical wiring systems of modern cars are expanded and constitute an important element of the entire vehicle structure. In electrical wiring systems, three basic circuits may be distinguished: energy supply, starting, and power supply to receivers. The electrical connectors currently used in vehicles can be divided into two groups. The main (and largest) part of the wiring is the *KSK* (*Kundenspezifischer Kabelbaum*). This is customer-specific wiring. This means that it is personalized by the customers, which are redundant wires, which would not be connected because the receivers were not ordered. The second type of the wiring used in vehicles is smaller, autonomous wiring attached to the KSK, the *Autark* (German for self-sufficient). Such smaller self-sufficient systems include, e.g., wiring of doors, roof, centre console, or rear hatch

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boot lid. Furthermore, it should be remembered that automotive wiring are not only electrical wires, but also electrical cubes, connectors, fuses, electrical connector, cable ties, cube seals, braids, mounting brackets, and many others **[L. 1–3]**.

Each type of wiring uses appropriate connectors to connect the various components of the electrical system. Electrical connecting lugs are used to easily connect the receiver and the electrical wire and ensure good conductivity between the connectors **[L. 3]**. There are two basic types of connectors: electrical connectors mounted to electrical cubes and electrical connectors used to ground, i.e. the ring lugs. To ensure a smooth and reliable electrical connection between receivers, the contact area of the electrical connectors is covered with high-quality metallic coatings, e.g., gold, silver, or tin.

The coating on the connector on the wiring side is matched based on the technical specifications of the receiver. This includes information on what kind of coating is applied to the male connector on the receiver side. This means that, if the receiver has a gold-plated male connector, the female connector on the wiring side must also be gold-plated. Not all electrical systems and receivers in vehicles are equally important and necessary for the safe operation of the vehicle. This is stated in the ASIL classification according to ISO 26262. Which coating is used on which connection depends on the importance of its function and the impact on passenger safety.

Components that are responsible for the safety of the vehicle occupants must work at all times and under all conditions. Reliability is required of them. Such systems have gold-plated connectors. Gold is a metal that does not corrode or oxidise, and the coating ensures accurate and fast data transmission between devices.

Silver is widely used in the electrical and electronics industries. It is used in the production of switches, contacts, or fuses, among others. Elements of high-importance systems, but not not as important as, e.g., safety systems, are coated with silver. In a passenger car there can be up to 40 switches which contain silver. These are, for example, elements of the engine start and control system, the steering system, brakes, or mirrors. Silver has particularly good electrical conductivity (better than copper) and good corrosion resistance (but worse than gold).

Most connectors are coated with tin. This is due to the price. Compared to gold and silver, the price of tin is much lower. Tin connectors link those receivers that do not affect safety systems. These are, for example, components qualified as ASIL A or ASIL B. Tin has a lower corrosion resistance than the previously mentioned elements. The combination of tin and copper or silver is very suitable for connecting electrical and electronic circuits; these connections have a synergy effect and are more durable.

Electrical connectors, like all vehicle components, are subject to damage. They cause interruption of the electrical circuit or data transmission, which results in incorrect functioning of a given receiver, and sometimes even the entire vehicle. The most common damages to connectors are corrosion, mechanical damage, cable tearing, and oscillating vibrations.

Corrosion is one of the most frequent causes of failure, and it may occur when a vehicle is flooded, e.g., due to heavy rainfall, flooding, or even when a windowpane is not fully closed. Very often, however, the corrosion processes are catalysed by humid air, and the wear processes may be accelerated by particles resulting from the vehicle operation **[L. 4]**. Additionally, small abrasive particles, such as mud, sand, or other particles, may get into the connector during its operation together with water, which accelerates the wear of protective anti-corrosive coatings applied on the connector contact surfaces.

Damage caused by vibration is also a serious failure. The most exposed are elements working in the area of the engine and elements transferring vibrations from the road surface on which the vehicle is moving. These vibrations cause connectors to make small movements of up to 0.2 mm, which, combined with corrosive factors, may lead to fretting **[L. 5, 6]**.

The aim of the conducted research was to determine the influence of corrosion processes on tribological properties of tin coatings applied on connector surfaces. Despite the high resistance of tin to the oxidation process, an intensive corrosion environment may cause the formation of a passive oxide layer on its surface **[L. 7]**. The resulting oxide layer has different properties from the substrate material. The occurring chemical transformations of the coating material may also influence the change of its tribological properties **[L. 8]**. The connection in electrical connectors is of a frictional nature, which ensures good contact and electrical conductivity. Therefore, it is important to have an appropriate value of the static friction coefficient, which keeps the connection immobile. In addition, the corrosive surface occurring on the surface may have a different wear resistance than the base material. As a result of the occurring vibrations, micro-slips or slips in case of loosening, tribo-corrosion wear may occur and the coating may be destroyed **[L. 6, 8]**.

Within the framework of the described research, the tribological properties of tin coatings in the non-oxidised and oxidised condition (after the corrosion process) were verified. The results obtained allowed evaluating the influence of corrosion on friction and wear of this type of coatings. An important aspect of the experiment was the application of an innovative method allowing for the determination of the static and kinetic friction coefficient and wear directly on coated products. Additionally, the tin coatings were subjected to metallographic analysis.

MATERIALS AND METHODS

Tribological and metallographic tests were carried out on lug connectors used as a wiring ground and fixed to a car frame or body. The tested connectors are made of copper and usually coated with tin.

Observations of microstructures and surfaces of the investigated coating in subsequent stages of the research were carried out using Phenom G2 and G2 ProX scanning electron microscopes, at magnifications ranging from 1000× to 10 000×. An accelerating voltage of 15 and 25 kV was applied during the tests. Observations were carried out in material contrast using SE and BSE detectors. Metallographic samples were prepared longitudinally and transversely to the plastic working direction, using grinding and mechanical polishing processes.

The chemical composition of the studied coating was analysed using an X-ray microanalyser coupled to Phenom G2 ProX scanning microscope. The results of the microanalyses were recorded graphically in the form of X-ray energy spectra graphs, which, due to the elements detected, were subjected to quantitative analysis using the ZAF correction method.

Tribological tests were carried out on connectors with newly applied tin coatings and on tin-plated connectors. The connectors were subjected to corrosion by immersion for a period of 1 year in a saturated aqueous solution of sodium chloride – NaCl (300 g/dm^3) at a temperature of 21°C. The connectors in their initial state and after the corrosion process are shown in **Fig. 1**.

Tribological tests were carried out on an alternating motion friction tester with an adapted test head **[L. 9]**. During the tests, a ceramic ball (SiC) with a diameter of d = 4 mm was pressed against the connector surface with a force of F_n = 15 N. Static friction factor (SCOF) tests were carried out on an intact surface each time. Wear tests were performed during 100 movement cycles at a speed of v_s = 10 mm/s. Each movement cycle consisted of two movements (back and forth) with length s = 3 mm each. During the life tests, the frictional force (F_T) was also recorded, which made it possible to analyse changes in the value of the coefficient of kinetic friction (COF) as the coating wore down. Static friction force was measured automatically during 5 one-way movements with 10 s intervals. The kinematic diagram of the friction node is shown in **Fig. 2**.

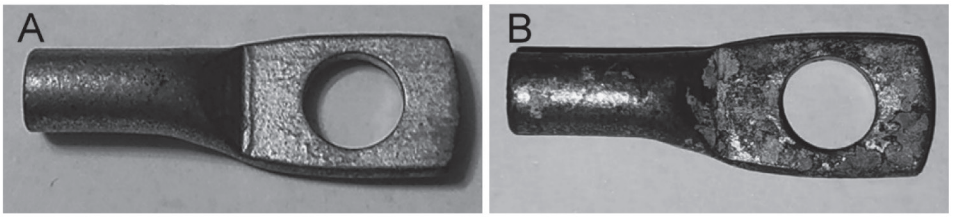

Fig. 1. Tested connectors: A) initial state, B) state after the corrosion process
Rys. 1. Końcówka konektorowa poddana badaniom: A) stan wyjściowy, B) stan po procesie korozyjnym

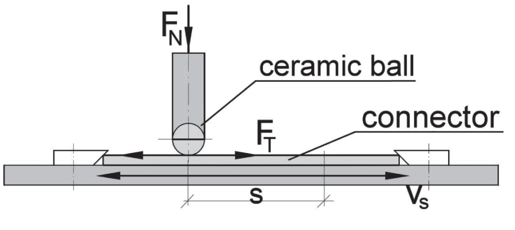

Fig. 2. Kinematic diagram of the applied plate-ball friction joint
Rys. 2. Schemat kinematyczny zastosowanego węzła tarcia w skojarzeniu płytka–kulka

Tests were performed 5 times under conditions of technically dry friction. Due to the use of a sensitive measuring system with strain gauges in the device and the use of step motors for the drive, it was possible to control movement cycles very precisely. Such a solution allowed us to perform tests on connectors of small size (about 10 mm long). The described method and test equipment have already been successfully used to test laser-annealed coatings **[L. 10]**.

RESULTS

In the first phase of the research, the quality of the tin coatings themselves was evaluated. Microscopic observation of the connector coating performed on the element cross-section showed the presence of a protective coating with thickness from 3 to 10 µm (**Fig. 4**). The observed coating was continuous along the whole length of the element, which was characterised by a high degree of development of the external surface and numerous defects in the form of pores and internal discontinuities (**Fig. 3**).

Tribological (wear) tests showed large differences in changes of the kinetic friction factor (COF) during the measurement run for non-corroded and new samples. Representative courses of changes for selected measurements in the form of moving average graphs are presented in **Figures 5–6**.

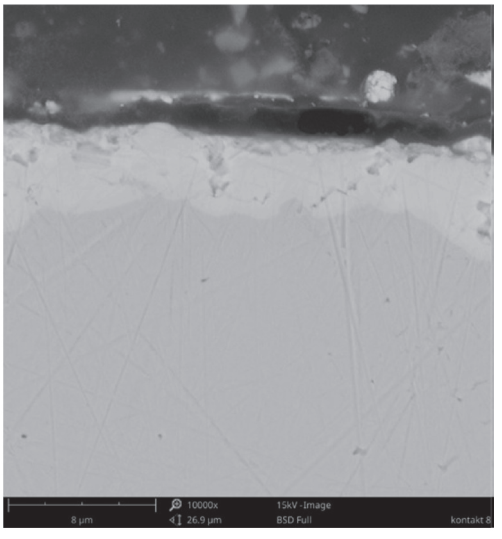

Fig. 3. Connector cross-section showing irregularities, numerous pores and discontinuities in the coating
Rys. 3. Przekrój poprzeczny konektora ukazujący nierówności, liczne pory i nieciągłości w powłoce

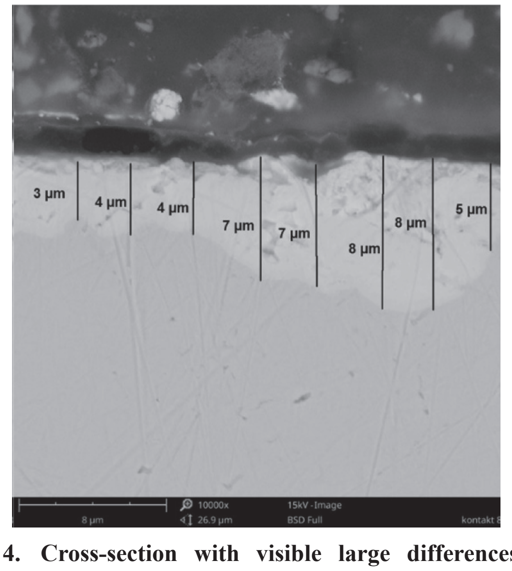

Fig. 4. Cross-section with visible large differences in coating thickness
Rys. 4. Przekrój poprzeczny z widocznymi dużymi różnicami w grubości powłoki

As can be seen in the case of samples in the condition after delivery (without oxide layer), the value of the friction coefficient increases significantly in the first phase of the test, and after reaching the maximum value (after about 30 cycles, 30 s), it decreases and remains constant.

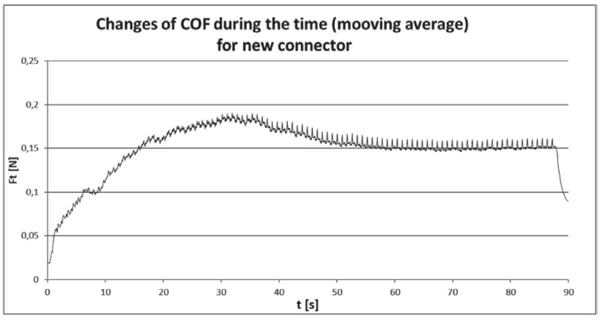

Fig. 5. A representative graph of changes in the moving average of the coefficient of friction during wear tests of connectors not subjected to corrosion
Rys. 5. Reprezentatywny przebieg zmian średniej ruchomej współczynnika tarcia podczas badań zużycia konektorów niepoddanych działaniu korozji

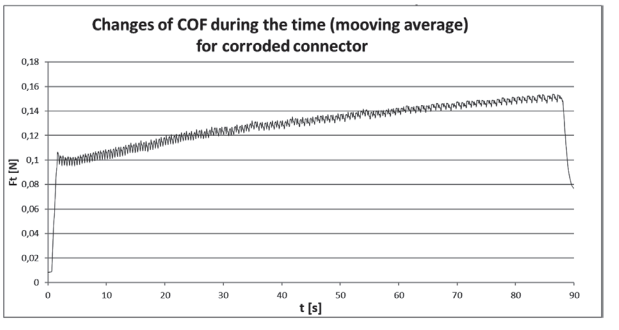

Fig. 6. A representative graph of changes in the moving average of the coefficient of friction during wear tests of connectors subjected to corrosion
Rys. 6. Reprezentatywny przebieg zmian średniej ruchomej współczynnika tarcia podczas badań zużycia konektorów poddanych działaniu korozji

In the case of corroded samples, the value of the friction coefficient increases linearly with the testing time.

Based on the static friction force tests, the mean values and standard deviation of the static friction coefficient (SCOF) and the maximum and minimum values of the kinetic friction coefficient (COF) were determined for the tested combinations. A summary of all results is presented in **Table 1**.

The obtained results clearly show that friction combinations with connectors without an oxide layer (new) are characterised by lower values of friction coefficients than for connectors with a corrosion layer. Moreover, the minimum recorded values of the kinetic friction coefficient are smaller for this case. Interestingly, the highest value of the kinetic friction coefficient occurred for new connectors ($\mu_{max} = 0.190$).

The values of the wear trace width measured on the friction surfaces clearly indicate less wear of oxidised surfaces in comparison with surfaces without an oxide

Table 1. Summary of friction coefficients values determined in tribological tests

Tabela 1. Zestawienie wartości współczynników tarcia wyznaczonych na podstawie badań tribologicznych

Sample	μ_0 Average SCOF	σ_μ Std. dev. of SCOF	μ_{min} Minimal COF	μ_{max} Maximal COF	*b* Wear path width
New connector	0.103	0.00167	0.055	0.190	355÷382
Corroded connector	0.111	0.00579	0.095	0.154	183÷232
	[-]	[-]	[-]	[-]	[µm]

layer. Based on the maximum values of the wear trace width, the cavity depth was estimated (knowing the diameter of the ceramic ball). For the non-oxidised layer with a wear width of 382 µm, the calculated wear depth was 9.1 µm. With a non-uniform coating thickness, this can result in complete abrasion of the coating in some places. In the case of connectors with an oxide layer, the wear depth was estimated at 3.4 µm with a track width of 232 µm. For this case, the minimum coating thickness value measured in the metallographic analyses is also abraded.

In order to evaluate the corrosion and life processes, the samples were subjected to microscopic observation after testing. The traces of wear and deformation of coatings for the tested connectors are presented in **Figs. 7** and **9**. Additionally, in order to evaluate the influence of corrosion on the worn surfaces, the microscopic analyses were supplemented with observations of worn and corroded surfaces. The observations from these analyses are shown in **Fig. 8**.

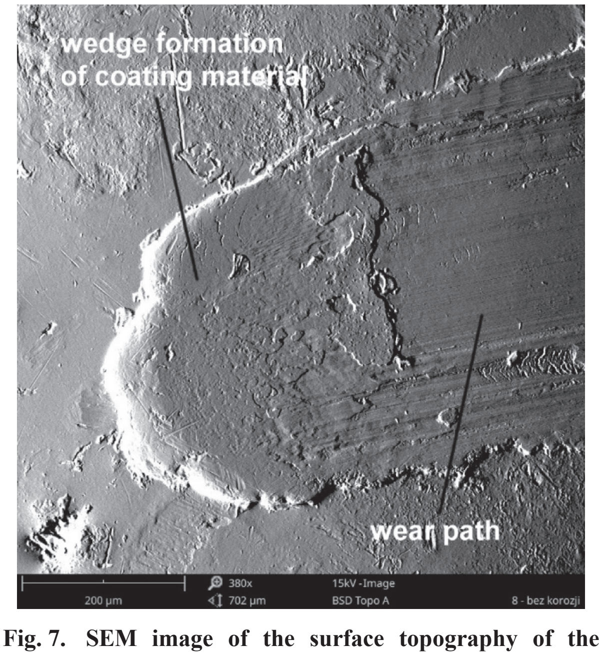

Fig. 7. SEM image of the surface topography of the abrasion trace of the non-corrosive connector surface

Rys. 7. Obraz SEM topografii powierzchni śladu wytarcia powierzchni konektora niepoddanego korozji

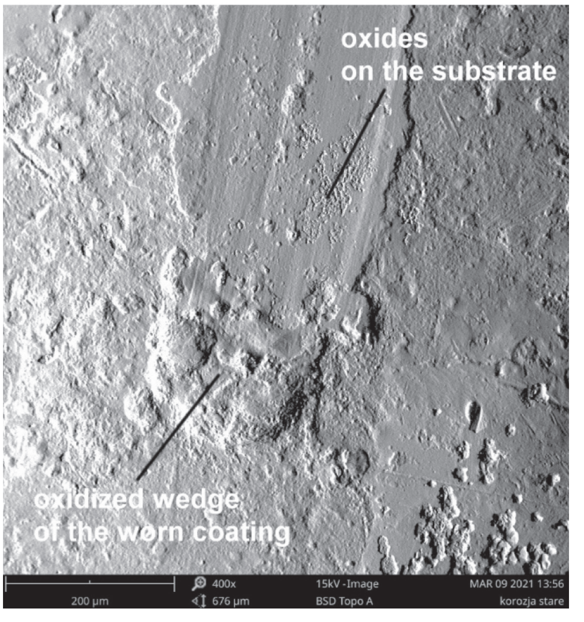

Fig. 8. SEM image of the surface topography of the abrasion trace of the surface of a new connector subjected to the corrosive process

Rys. 8. Obraz SEM topografii powierzchni śladu wytarcia powierzchni nowego konektora poddanego procesowi korozyjnemu

The microscopic observations showed a strong influence of corrosion on the friction and wear process of the tin coatings. In case of a new component, without the oxide layer, plastic deformation of the coating is clearly visible (**Fig. 7**). The traces of furrowing and formation of tin pileups at the ends of friction path can be observed. Interestingly, the exposed copper substrate is not clearly visible in the photographs taken. This may be due to the good adhesion between the tin and copper, which, despite significant deformation, causes only local discontinuity of the coating and exposure of the substrate. This is confirmed by the results of observations made on connectors subjected to the wear process and only then to the corrosion process (**Fig. 8**). In the places of coating discontinuity, areas of copper oxide appeared.

Photographs of areas subjected to friction on the corroded surface clearly show the brittle nature of the resulting tin oxide layer (**Fig. 9**). The oxide layer becomes detached from the rest of the coating as a result

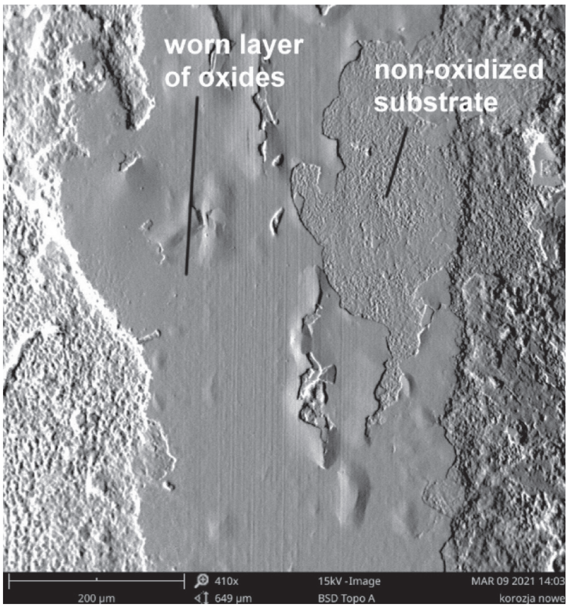

Fig. 9. SEM image of the surface topography of the abrasion trace on the surface of the connector subjected to the corrosion process

Rys. 9. Obraz SEM topografii powierzchni śladu wytarcia na powierzchni konektora poddanemu procesowi korozyjnemu

of friction. The oxide layer shows clear traces of abrasive wear (scratches). It can be assumed that the hard oxide layer protects the rest of the coating from wear, but due to poor adhesion to the rest of the substrate, it can become chipped. Such a mechanism favours the tribo-corrosion process and faster wear of the coating **[L. 8**, **11]**.

DISCUSSION AND CONCLUSION

Microscopic and tribological tests carried out show high adhesion of tin coatings to copper substrate, which is also confirmed by other researchers **[L. 12]**. The friction and wear mechanisms are strongly dependent on the presence of an oxide layer on the surface of the tin coating. The hard oxide layer formed due to corrosion limits the plastic deformation of the existing coating. Tribological tests have shown that the largest range of the friction coefficient occurred in the case of new connectors, which also confirms the occurrence of significant deformation of the coating as friction occurs and the contact area increases. Stabilisation of the friction coefficient value (**Fig. 5**) is probably caused by abrasion of the soft tin layer and frictional cooperation with the copper substrate. Increasing the contact area is the result of plastic deformation of the soft coating, which is also confirmed by SEM image analyses.

The oxidation layer limits the actual contact area. The pressures induced by contact with the ceramic ball are distributed over a larger surface area and reduce plastic deformation. This wear mechanism is indicated by the steady increase in frictional force during life tests (**Fig. 6**). The hard oxide surface also reduces wear of the coating compared to a surface without an oxide layer. Although the oxide layer protects the coating from abrasive wear, it negatively affects the electrical conductivity **[L. 12]** at the connector contact. A similar wear mechanism found during tests of other oxidised metallic surfaces was described in **[L. 8]**.

The brittle nature of the tin oxide and the low adhesion to the tin coating may be the cause of the tribo-corrosion wear mechanism, which will certainly have a negative effect on the durability of the coating. It should be noted that in the conducted tests the oxide layer was obtained only by chemical measures. In the case of electrical connectors during normal operation, there is also an electrical impact, which will certainly accelerate the corrosion process and the possible tribo-corrosion wear mechanism.

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