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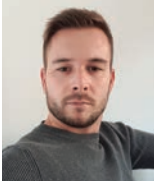
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Adhesion and anticorrosive properties of DTM coating as related to primer coating

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Professional paper

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High worldwide prevalence of steel in the construction of buildings and infrastructure is associated with high costs that are due to the sensitivity of steel to corrosion. To reduce the steel structure corrosion protection costs, great efforts are currently made to develop new technologies that would reduce working time and extend service life of corrosion protection systems. Due to an increasing use of the "direct to metal" (DTM) system for corrosion protection of steel structures, this system was tested in the scope of this study and compared with the systems involving the use of primer coating. The tests were carried out on three types of corrosion protection systems.

Key words:

corrosion, coating, adhesion, delamination, steel, DTM, direct to metal

Stručni rad

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Prionjivost i zaštitna svojstva DTM premaza u odnosu na premaze s temeljnim slojem

Velika zastupljenost čelika u izgradnji objekata i infrastrukture danas u svijetu uzrokuje velike troškove zbog osjetljivosti čelika na koroziju. Kako bi se smanjili troškovi zaštite čeličnih konstrukcija od korozije, ulažu se veliki naponi u razvijanje novih tehnologija kojima se želi smanjiti vrijeme rada i produžiti vijek antikorozivne zaštite. Uzimajući u obzir sve češću primjenu "direct to metal" (DTM) sustava za antikorozivnu zaštitu čeličnih konstrukcija, u radu je ispitana i uspoređena prionjivost ovog sustava sa sustavima s temeljnim premazom. Ispitivanja su provedena na tri tipa sustava antikorozivne zaštite.

Ključne riječi:

korozija, premaz, prionjivost, delaminacija, čelik, DTM, direktno na metal

Fachbericht

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Haftung und Schutzeigenschaften von DTM-Beschichtungen im Vergleich zu Beschichtungen mit einer Basisschicht

Die hohe Verbreitung von Stahl im Bau von Anlagen und Infrastrukturen verursacht in der heutigen Welt hohe Kosten aufgrund der Korrosionsempfindlichkeit des Stahls. Um die Kosten für den Korrosionsschutz der Stahlkonstruktionen zu senken, werden große Anstrengungen unternommen, um neue Technologien zu entwickeln, die die Arbeitszeit verkürzen und die Lebensdauer des Korrosionsschutzes verlängern sollen. Angesichts der zunehmenden Anwendung des Systems „Direct to Metal“ (DTM) zum Korrosionsschutz von Stahlkonstruktionen wurde in der Abhandlung die Haftung dieses Systems für Systeme mit einer Basisbeschichtung untersucht und verglichen. Die Tests wurden an drei Arten von Korrosionsschutzsystemen durchgeführt.

Schlüsselwörter:

Korrosion, Beschichtung, Haftung, Delamination, Stahl, DTM, direkt auf Metall

1. Introduction

Corrosion can in simplest terms be defined as an unintended wear of material caused by physicochemical, physical and biological agents. According to this general definition, the following materials can be affected by corrosion: stone, wood, and glass. However, corrosion is a phenomenon that is primarily related to chemical destruction of metals. According to corrosion mechanism, these processes are divided into two basic groups:

- chemical or "dry" corrosion occurs in nonelectrolytes on metals;
- electrochemical or "wet" corrosion occurs in the presence of electrolyte on metals and constitutes a huge problem for steel structures and their stability.

Corrosion reduces life span of structures, increases investment costs and structure maintenance costs, and causes delays and losses in production processes. Inadequate maintenance and neglect of corrosion phenomenon may lead to: loss of stability and bearing capacity of structures, loss of human lives, and environmental disasters [1].

We are currently required to spend much more time and money for corrosion protection than was earlier the case. This is due to several reasons [2]:

- greater presence and use of metals in all areas
- greater design accuracy and more rational use of metals in structures, resulting in structures that are susceptible to corrosion
- increasing use of high value metals requiring expensive and special corrosion protection due to their use in specific conditions
- higher corrosivity of environment due to global pollution.

The most frequently used and the most efficient corrosion protection (CP) agents for steel are organic and inorganic

coatings that are generally called paints. Paints have been used since the very beginning of mankind, and the first use is visible in caves inhabited by humans in prehistoric times. However, paints have assumed their proper role in CP not earlier than with the development of industrial revolution. Interestingly, according to NACE Corrosion Costs Study presented in 2016, as many as 3.45% of the total GDP of the US is used for the repair of direct damage caused by metal corrosion [3]. A part of these funds is used for the maintenance of the Golden Gate Bridge in San Francisco (Figure 1), which is continuously being coated with the recognisable "International Orange" paint. As the bridge is heavily exposed to atmospheric corrosion (high salinity levels, fog), a maintenance crew performs appropriate activities each day in order to slow down deterioration of structural elements, and to provide for a long service life of this bridge [4, 5].

A new problem, linked to development of environmental awareness, occurred at the onset of the new century: coatings previously used for corrosion protection of steel have proven to be harmful to environment. Newly developed environment-friendly water based coatings, presenting minimum damage to environment due to low proportion of volatile organic compounds (VOC), are nowadays extensively used for corrosion protection of steel structures. In addition, rapid development of nanotechnology has resulted in the development of a new generation of CP coatings that are capable of "closing" microcracks and repairing damage caused during transport, assembly, and use [6, 7].

In the light of the above considerations, the objective of current international research in the field of corrosion protection is to cut down financial cost by reducing time needing for coating work, and by extending maintenance intervals. The reduction in time needed for coating work implies the time for surface preparation, time for applying protective coats, and drying time for individual corrosion protection coats.

The corrosion protection process can be accelerated, and the price for application and maintenance of CP systems can be reduced, by the development of new systems (DTM) that do not require both primer and final coats. As the function of the primer is to ensure proper adhesion of corrosion protection coating, the quality of the new systems will be tested in the paper, and comparison will be made with systems with primer.

The influence of surface preparation and primer types on the quality of corrosion protection activities is studied in [8, 9]. These studies have revealed that the best quality of corrosion protection can be achieved on surfaces prepared by sandblasting and, with regard to prime coats, the best results were obtained with epoxy-polyamide coats.



Figure 1. Corrosion protection – a never ending activity at the Golden Gate Bridge

1.1. General information on DTM coatings

As already indicated, DTM coats are applied in a single or, exceptionally, in several coats in case of high corrosivity of the area in which DTM coating is used. Thus, these corrosion protection systems for steel must achieve, in a single coating, all that is normally achieved in two or more coats, i.e.: good adhesion to metal surface, resistance to corrosion, resistance to UV radiation, hardness, and aesthetic properties including gloss and durability. As all these conditions must be met in a single coating, this technology constitutes a big challenge for chemists to meet stringent requirements imposed by the market. DTM coatings are mainly classified according to the type of solvent: water based coatings and solvent based coatings. Depending on the type of binder, the coatings can be: epoxy, polyurethane, acrylic, and alkyd. The most frequently used DTM protection systems are water based acrylic systems with epoxy or polyurethane binders. They have been developed as a result of the EU directive 2004/42/EZ and the Commission Directive 2010/79/EU for the reduction of VOC in CP systems [10, 11]. Future development of protective coatings will be oriented toward full elimination of VOC from CP coatings [12].

A considerable drawback of such systems is that they are still under development, and the formula that would meet all requirements has not as yet been developed. One of such requirements for civil engineering structures is good adhesion and the lowest possible class of delamination due to damage occurring in the course of assembly work. Concentrated efforts are presently made to adjust chemical composition in order

to improve adhesion properties while keeping other good properties [11, 13, 14]. Currently, the systems are most often used as coatings for pipes, tanks, handrails, steel doors, and railway carriages, while they are also used in automobile, civil engineering, and transport industries.

The fact that DTM is currently finding its place on the global market for metal coatings is further evidenced by the annual growth estimate of as much as 10%, while the entire market is estimated to grow at the rate of 4.5% [15].

1.2. Selection of corrosion resistant coating

A proper corrosivity category of the environment in which the structure is situated must be defined so as to enable selection of a proper corrosion resistant coating. The environment categories as related to their influence on metal degradation are specified in ISO 12944-2 [16], as shown in Table 1.

When selecting the environment corrosivity category, it is very important to define conditions in which the structure will be used during its service life. The conditions influencing environment corrosivity class are: air temperature and humidity, UV radiation, exposure to chemical hazards and mechanical damage. By considering these conditions, a structure can be classified into one out of six corrosivity categories specified in ISO 12944-2.

These six environment corrosivity categories are defined for structures exposed to atmospheric influences. Four corrosivity categories, presented in Table 2, are defined in ISO 12944-2 for

Table 1. Atmospheric corrosivity categories

Corrosivity category	Examples of typical environments	
	Exterior	Interior
C1 very low	-	Heated buildings with clean atmospheres, e.g. offices, shops, schools, hotels
C2 low	Atmospheres with low level of pollution. Mostly rural areas	Unheated buildings where condensation may occur, e.g. depots, sports halls
C3 medium	Urban and industrial atmospheres, moderate sulphur dioxide pollution. Coastal areas with low salinity	Production rooms with high humidity and some air pollution, e.g. food-processing plants, laundries, breweries, dairies
C4 high	Industrial areas and coastal areas with moderate salinity	Chemical plants, swimming pools, coastal ship- and boatyards
C5 very high	Industrial areas with high humidity and aggressive atmosphere	Buildings or areas with almost permanent condensation and with high pollution
CX extreme	Offshore areas with high salinity, industrial areas with extremely high humidity and aggressive atmosphere, and subtropical and tropical atmospheres	Industrial plants with extremely high humidity and aggressive atmosphere

Table 2. Corrosivity categories for structures immersed in water or buried in soil

Corrosivity category	Environment	Examples of environments and structures
Im1	Fresh water	River installations, hydroelectric power plants
Im2	Sea or brackish water	Immersed structures without cathodic protection, such as: sluice gates, locks or jetties
Im3	Soil	Buried tanks, steel piles, steel pipes
Im4	Sea or brackish water	Immersed structures without cathodic protection, such as: offshore structures

structures immersed in water or buried in soil. The corrosivity category of an immersed structure depends on the type and chemical composition of water and, for buried structures, the corrosivity category depends on moisture and presence of bacteria.

Although the selection of coating according to the type of environment corrosivity is one of the most important steps, the already mentioned maintenance intervals for CP structures are also significant for determining the price of maintenance of structures. Depending on CP renovation intervals, four CP durability classes have been defined in ISO 12944-1 (Table 3).

Table 3. Corrosion protection durability classes

Durability class and symbol	Time period
Low - L	up to 7 years
Medium - M	from 7 to 15 years
High - H	from 15 to 25 years
Very high - VH	more than 25 years

2. Preparation and testing adhesion of corrosion resistant coating

An appropriate testing campaign was conducted in the Laboratory of Materials Protection of the Faculty of Mechanical Engineering and Naval Architecture – University of Zagreb in order to estimate adhesion and durability of DTM systems. Two sample types were prepared for adhesion testing: the first group of samples was cleaned by hand to the cleanliness of St3 according to ISO 8501-1 [17] and the second group was cleaned mechanically by sandblasting to the cleanliness of Sa 2^{1/2} according to the same standard. The testing was conducted on steel samples S 235JR, measuring 100 mm x 150 mm, 5.0 mm in thickness. As the objective was to determine latest advances in the quality of new products without primer, two additional systems with primer were tested in addition to the DTM system. The following products manufactured by Colorificio Damiani

[18] were used in the testing: *Epoprimer FZ* was used for primer, *Neutro 4500 SL* was used for finishing coat, and *Neutro Fosfacryl* was used for DTM coating.

The samples were divided into three groups according to the coating system, and into two subgroups according to the type of prepared surface, as shown in Table 4. Each subgroup is made of five samples.

The first protection system (Group 1) selected for the testing was a standard system applied for exposure class C3-M. The system is composed of: the epoxy prime coat 60 µm in thickness and the polyurethane finish coat 80 µm in thickness. The second protection system (Group 2) selected for the testing is applied for exposure class C5-M. The system is composed of: the epoxy prime coat 60 µm in thickness, epoxy mid coat 100 µm in thickness, and the polyurethane finish coat 80 µm in thickness. The third protection system (Group 3) consists of two phosph. acrylic coatings 60 µm and 80 µm in thickness, respectively. Each coating system has two subgroups depending on the type of surface on which it is to be applied, as described above.

The adhesion and durability of CP systems were tested using an accelerated corrosion testing conducted in a humidity and salt spray chamber. After the testing in this humidity and salt spray chamber, the adhesion was tested using the cross-cut method and then, the delamination class was determined. The hardness and coating thickness was measured on all samples before the start of the testing in chamber. The samples were also subjected to the following tests: gloss testing and UV chamber testing [19]. However, due to space limitations, and because of irrelevance for the durability and adhesion testing, these additional tests are not presented in the paper.

2.1. Coat thickness measurement

Coat thicknesses were measured for all samples according to HRN EN ISO 2808 [20]. The coat thickness measurements were conducted in order to check thickness of the dry film, and to determine whether the necessary CP thickness – based on manufacturer's recommendations – was applied for the defined environment corrosivity classes. Ten measurements were made

Table 4. Sample groups prepared for laboratory testing

Group No.	Surface preparation symbol	Surface preparation	Coating system
1	A	Manual cleaning	Epoxy primer 60 µm + polyurethane finishing coat 80 µm
	B	Mechanical cleaning	Epoxy primer 60 µm + polyurethane finishing coat 80 µm
2	A	Manual cleaning	Epoxy primer 60 µm + epoxy intermediate coat 100 µm + polyurethane finishing coat 80 µm
	B	Mechanical cleaning	Epoxy primer 60 µm + epoxy intermediate coat 100 µm + polyurethane finishing coat 80 µm
3	A	Manual cleaning	Phosph. acryl coat 60 µm + 80 µm
	B	Mechanical cleaning	Phosph. acryl 60 µm + 80 µm

for each sample using the Elcometer 456/4 device (Figure 2). The ten measurements per sample were reduced to an average coating value, and the results obtained were presented in graphic form (Figure 3).

According to manufacturer's recommendations, 140 μm of dry film had to be applied for samples belonging to group 1, and the values from 124 μm to 160 μm were obtained by actual thickness measurements. According to manufacturer's recommendations, 240 μm of dry film had to be applied for samples belonging to group 2, and the values from 227 μm to 275 μm were obtained by thickness measurements. According to manufacturer's recommendations, 140 μm of dry film had to be applied for samples belonging to group 3, and the values from 122 μm to 157 μm were obtained by thickness measurements. Measured thicknesses smaller than those defined according to manufacturer's instructions would not exert a considerable influence on results, as the primary objective of the study was to determine the quality of adhesion of the group 3 system, compared to adhesion of group 1 and group 2 systems. Consequently, all samples with coat thicknesses complying with specified thicknesses were retained for further testing.



Figure 2. Coat thickness measurement

2.2. Coating hardness testing

The coating hardness was tested so as to check resistance to wear. Resistance to wear is a significant property imposed on coatings so that their proper integrity during service life can be ensured. If hardness of a coating is low, then the coating is susceptible to damage.

The hardness testing is conducted in accordance with ISO 15184:2013 [21]. Six pencils (Wolff-Wilborn method) of varying graphite lead hardness, ranging from 6H (the hardest) to 6B (the softest), are used. The measuring equipment consists of: Simex instrument that ensures proper pencil positioning at an angle of 45° with respect to the surface, and 14 pencil leads of varying thicknesses (Figure 4). The test starts by using the hardest pencil lead and continues toward softer ones. The first lead that does not leave any trace on the surface denotes the coating hardness. The coating hardness is classified according to ISO 15184 as follows: the coatings on which pencil leads leave no trace in the interval from 6H to 3H, from 2H to 2B, and from 3B to 6B are classified hard, medium, and soft, respectively.



Figure 4. Coating hardness measurement on samples

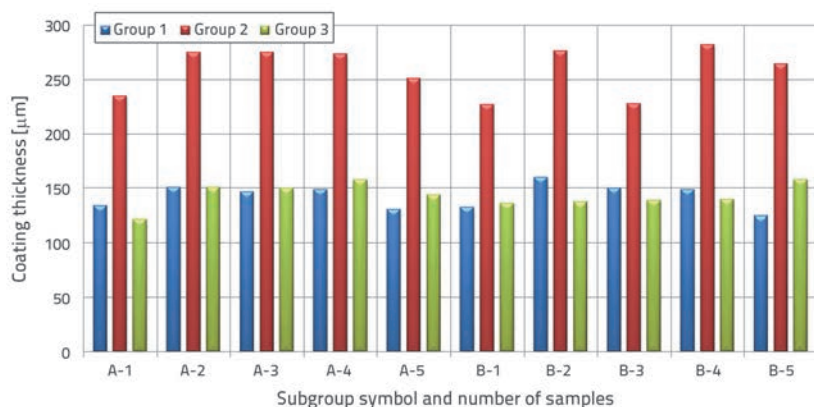


Figure 3. Measured thicknesses of CP coatings

During the hardness testing, the pencil H1 did not leave any trace on the surface of any the coating samples tested. The results obtained during this testing show that all CP systems exhibit equal hardness, and that they belong into the medium hardness category.

2.3. Testing in salt spray chamber

The salt spray chamber testing is performed to simulate sample exposure to sea atmosphere. During this test, the NaCl solution is sprayed as mist onto the samples. The testing was conducted

Table 5. Salt chamber test results

Group No. / Sample mark test	1-A	1-B	2-A	2-B	3-A	3-B
Delamination class	2	1	1	1	5	3
Adhesion assessment	1	0	1	0	1	0

in accordance with HRN EN ISO 9227:2012 [22], and the salt chamber Ascott, model S450, was used in the testing. The samples were tested in salt chamber for 240 h, which corresponds to the environment corrosivity category C3-M, according to ISO 12944-2. Before the samples were placed into the chamber, each one was notched according to EN ISO 7253 [23] so as to speed up the corrosion process (Figure 5). After the testing, the samples were taken out of the chamber and subjected to visual inspection. This inspection revealed that no corrosion occurred in the area where the coating was complete, and that all three CP systems are stable and compliant with the corrosivity category C3-M. The analysis of CP stability of group 1 samples in the zone around the scribe revealed very small blistering at subgroup A (samples with hand-cleaned surface), while no blistering was observed at subgroup B. It was established by sample testing according to EN ISO 4628-8:2005 [24] that the samples

included in subgroups A and B belong to delamination classes 2 and 1, respectively (Table 5). The analysis of stability of CP samples belonging to group 2 in zone around the notch did not reveal any blistering or damage in both subgroups, and so this system can be classified as belonging to delamination class 1 according to EN ISO 4628-8:2005. The coating system 3, which was characterized by good stability on the entire part, actually exhibited considerable blistering in both subgroups in the zone around the scribe. According to EN ISO 4628-8:2005, the damage to samples belonging to subgroups A and B belonged to the delamination classes 5 and 3, respectively (Figure 6). The adhesion was determined on all samples by cross-cut test according to HRN EN ISO 2409:2013 [25]. The testing revealed that adhesion was good on all samples (Table 5). For all samples belonging to subgroups A and B, test results can be reduced to average adhesion values of 1 and 0.



Figure 5. Sample testing in salt spray chamber



Figure 6. Determination of delamination level after salt spray chamber testing



Figure 7. Sample testing in humidity chamber

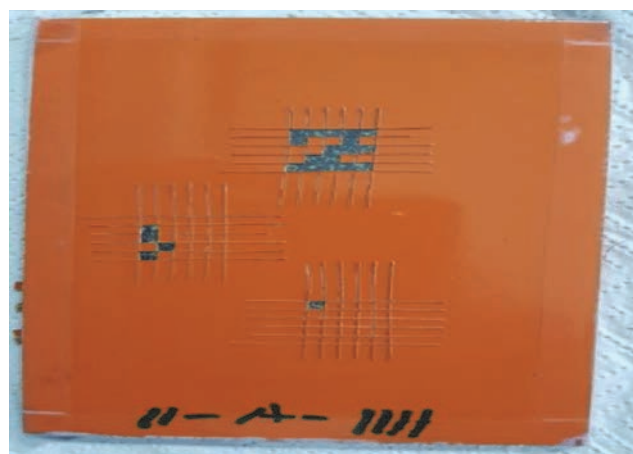


Figure 8. Cross-cut testing after humidity chamber

Table 6. Cross-cut test results

Group No.	1-A	1-B	2-A	2-B	3-A	3-B
Sample mark test						
Adhesion assessment	1	0	4	0	1	0

2.4. Humidity chamber testing

The CP behaviour in humid and warm atmosphere with water condensation was simulated by humidity chamber testing (Figure 7). The tests were conducted according HRN EN ISO 6270-2:2007 [26]. During the testing, the temperature in chamber amounted to 40 ± 3 °C, and the relative air humidity to about 100%, with sample misting.

The testing was conducted for 240 h, which corresponds to the environment corrosivity category C3-M, according to ISO 12944-2. After the testing, the samples were subjected to visual inspection and it was established that CP systems suffered no visible damage. The results obtained in humidity chamber for all three system show that they are stable at humid and warm atmosphere and that they comply with requirements for the corrosivity category C3-M.

Visual assessment was followed by cross-cut testing according to HRN EN ISO 2409:2013. Good adhesion results were obtained on all three CP samples by cross-cut analysis (Table 6). Similar to the results obtained on samples tested after salt spray chamber, average adhesion values of 1 and 0 were obtained by cross-cutting for samples belonging to subgroups A and B, respectively. However, an exception was observed during cross-cutting for a coating system 2 sample belonging to subgroup A, which obtained the adhesion value of 4 at one point, while much better results were obtained during two subsequent tests on the same sample (Figure 8). The poor adhesion obtained on this sample can be explained by local surface impurity that was not degreased prior to application of the primer. This explanation is backed by the fact that the remaining subgroup B samples exhibited good adhesion. The results obtained on the sample 2-A should be understood as indicators of unreliability of CP testing when the surface has been cleaned manually. The influence of proper surface preparation on the quality of CP testing is investigated in [8].

3. Conclusion

The corrosion protection systems involving a combination of epoxy primer and polyurethane finish coating have proven to be an excellent protection of steel structures against atmospheric corrosion, both based on practical application and laboratory testing. This research has confirmed the quality of epoxy primer and its exceptionally good adhesive properties, when applied on either a mechanically or manually prepared surface. The results obtained show that epoxy primer prevents delamination, i.e. propagation of corrosion under the coating in the zone around a damage, as has already been proven in a number of experimental studies. The results obtained by testing the DTM system of a selected manufacturer show that the coating is susceptible to strong delamination in the zone around the damage. The DTM delamination occurred regardless of the quality of surface, it is highly pronounced, and unacceptable when compared to the systems with primer. The adhesion test results for manually cleaned surfaces point to the unreliability of CP coating applied on such surfaces.

It can be concluded based on this testing that the DTM coating applied offers a good quality corrosion protection in the environment category C3-M, but it is more prone to delamination in the zone around the damage. Compared to the two-layer coating systems, the DTM system does not offer a reliable protection in the case of steel structures that are exposed to mechanical damage during assembly.

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