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INFLUENCE OF ROUGHNESS OF MACHINED SURFACE ON ADHESION OF ANTICORROSION SYSTEM

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Abstract

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The goal of this experiment is to analyse dependence of roughness of machined surface on adhesion performance of various anticorrosion systems. In order to prepare samples for the experiment, samples were milled on a knee and column type of a horizontal milling machine. Depending on cutting conditions and machining tool, there were set intervals of roughness of machined surface which are commonly achievable on this type of machine. It is a roughness in the interval of 0.4–1.6 µm (finishing), 1.6–6.3µm (standard milling) a 6.3–12.5µm (roughening). Removable cutting tips were used as a machining tool and for roughening, a shell end milling cutter NAREX 63x40 HSS 90 was used.

Three types of anticorrosion systems were used in order to analyse the adhesion, that is a water-thinnable system Eternal, synthetic single layer coating Hostagrund and a duplex system, whose first layer is formed by dipped zinc and a top layer by a single-layer acrylate system Zinorex. Testing of the influence of surface roughness (anchoring system) on adhesion of the individual anticorrosion systems were processed in compliance with the norm ČSN EN ISO 4624, a tearing test. The main criterion of adhesion of anticorrosion system is defined as a power which needed for tear-off testing object stuck to a tested sample. This analysis was processed also during the corrosion test in the salt spray environment according to the norm ČSN EN ISO 9227. In order to better identify the adhesion of the individual anticorrosion systems, the analysis of undercorrosion according to the norm ISO 4628-8 was processed.

surface roughness, corrosion, adhesion, cutting operation

Current trend of production of machine parts is cutting operation, which world-wide forms about 70 % of production of machine parts.

Machined surface is absolutely not ideally soft (Dillinger, 2007; Stachowiak, 2005). It shows a certain level of roughness, which is defined by microroughness originating in the machining process. For example, an inadequate surface roughness causes an inadequate degradation of sides of cog-wheels (Andrássyová, 2010). If a machine part is not limited by shape or geometrical tolerance, the surface roughness forms a final anchoring profile for application of anticorrosion protection. As after the anticorrosion protection was applied there may occur that the protective layer peels off, the anchoring profile is one of the main criteria observed before application of organic coating composition.

Corrosion degradation of not only metal elements depreciates any machine part. It does not necessarily be a massive material decrease, but corrosions consists also in degradation at the level of intercrystalline and transcrystalline grain crack (Bartoníček, 1980).

Organic and inorganic coatings are the most common types of anticorrosion protections. Quality of the individual coatings are affected by the not only by the preparation of the base material (mechanical and chemical cleaning), but also anchoring profile which guarantees a tight connection of the anticorrosion system with the base material (Trethewey, 1995).

As the authors of technical literature differ in their opinions of recommended values of roughness for different anticorrosion systems, the aim of this paper is to analyse the influence of machined surface (its anchoring profile) on adhesion of anticorrosion systems standardly used in engineering. Moreover, the anchoring profile is the main criterion for preparation of duplex coatings, where metal coating is being combined with an organic paint (Matejka, 1989). The organic paint has to be dedicated to an application to an anticorrosion coating; otherwise it would lead to a premature degradation in the form of peel-off.

MATERIAL AND METHODS

Samples were prepared from steel C45E nominated according to the norm ČSN 12050. It is steel with a mid composition of carbon, see Tab. I, which is appropriate for mid stressed machine parts. This steel performs a good machinability even at worsened cutting conditions (machining without cooling).

In order to improve mechanical characteristics of the steel, heat treatment was processed – heating was by 45 °C higher than the Ac_3 curve. It is a normalization process with a gradual cooling at air. The mentioned heat treatment was also processed in order to improve the quality of machined surface.

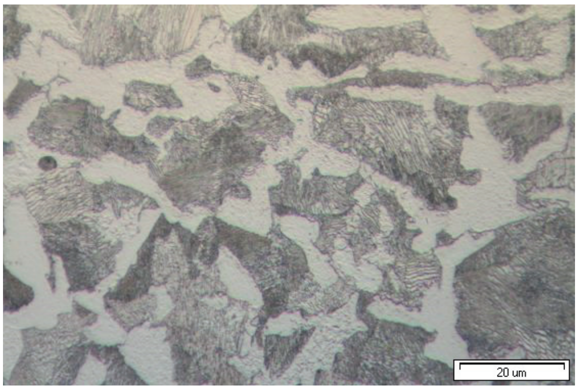
Improvement of mechanical performance after heat treatment is determined by grain smoothening and even distribution of soft and even carbides. As it is apparent from Fig. 1, after heat treatment the dispersity of pearlite lamellas has increased which results into a higher steel toughness.

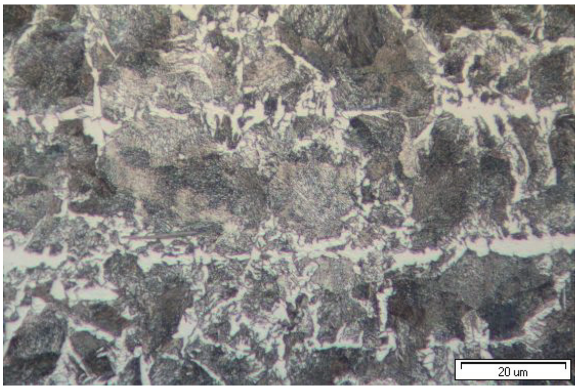
After heat treatment, there were prepared samples sized 70 × 50 × 5 mm, which were afterwards machined on a vertical knee and column type of milling machine using a milling cutter 63A06R with removable cutting tips. In order to achieve higher roughness of machined surface, there was used a shell end milling cutter NAREX 63x40 HSS 90. Technical parameters of removable cutting tips can be found in the Tab II. Parameters of a shell end milling cutter NAREX 63x40 HSS 90 are recorded in Tab. III.

The intention of using removable cutting tips with a different radius of cutting edges was to achieve different roughness Ra of the machined surface. In order to achieve desired roughness Ra, there were used also different cutting conditions during the machining process. Cutting conditions form

I: *Chemical composition of steel C45E (Řasa, 2007)*

Name according to the EN norm	Chemical composition [%]									Transition points [°C]			
	C	Mn	Si	Cr	Mo	V	W	Ni	Oth.	Ac_1	Ac_3	Ar_1	Ar_3
C45E	0.42	0.50	0.17	0.25	-	-	-	0.30	-	720	780	725	785





1: *Steel C45E: without heat treatment (left), normalized (right)*

II: *Removable cutting tips*

Name	Hardness [HRC]	Size [mm]				
		l	*d*	*s*	d_1	r_ε
ADMX160608SR	75	16.00	9.95	6.25	4.50	0.80
ADMX160632SR	75	16.00	9.95	6.25	4.50	3.20

III: *Technical parameters of a shell end milling cutter NAREX 63x40 HSS 90*

Name	Material	Size [mm]			
		D	*d*	*L*	*z*
NAREX 63x40 HSS 90	19 830	60	27	40	12

the main criterion for production effectiveness (Žitňanský, 2004; Gorczyca, 1987; Marek, 2010).

Roughness Ra of machined surfaces was measured on the level linear to the movement of rotating tool. For measurement a scoring unit SJ-201 with the accuracy 0.01 µm was used.

Both a shell end milling cutter and removable cutting tips are widely used in technical practice. In the cutting operation it is necessary to cutting conditions. As shell end milling cutter is made of high-speed steel 19 810, the cutting speeds must be lower comparing to the materials of sintered carbide. Breaking cutting conditions may cause defect or destruction of the whole tool.

In order to observe the influence of adhesion depending on anchoring profile of a machined surface, there were selected three different anticorrosion systems:

- water-thinnable paint "Eternal",
- synthetic coating composition "Hostagrund",
- duplex system – hot dipped zinc + "Zinorex".

Further, there was tested the influence of surface roughness (anchoring profile) on adhesion of the individual anticorrosion systems. The analysis was processed in compliance with the norm ČSN EN ISO 4624, in which the tearing test of adhesion of paint systems is being defined.

This analysis was supplemented by results of corrosion test according to the norm ČSN EN ISO 9227 (salt-spray test). In order to observe the development of degradation of an anticorrosion system, the tearing test according to the norm ČSN EN ISO 4624 was processed in the given time intervals of 10, 20 and 30 days.

Untercorrosion of anticorrosion system according to ISO 4628-8 was analysed as well. It is a test monitoring corrosion around an artificially created defect (scratch).

RESULTS AND DISCUSSION

Setting cutting conditions to optimise surface roughness

Surface roughness is one of the main criteria to assess the quality of machined surface. The roughness may be caused by e.g. a machining tool, a swage or a sand mould (Žitňanský, 2005; Němec *et al.*, 2006). These inequalities form an anchoring profile for application of the anticorrosion protection. Based on results of experimental measurements, there were set optimal cutting conditions in order to achieve the desired roughness of machined surface.

Cutting speed v_c was counted according to the below mentioned relation:

$$v_c = \frac{\pi \times D \times n}{1000}, \qquad [\text{m}\cdot\text{min}^{-1}]$$

where:
D ... diameter of a tool [mm]
n .... number of turnings [min^{-1}].

The minute movement of cutting tips was 100 mm·min^{-1} (gear ratio: 112) and the movement of HSS 90 was 40 mm·min^{-1} (gear ratio: 40), see Tab. IV.

Surface roughness of the individual samples was divided into three intervals corresponding to the most common cutting operation in engineering production. This division is standardly mentioned in engineering literature (Juneja, 2003; Hluchý, 2001). It is cutting operation in the intervals of 0.4–1.6 µm, 1.6–6.3 µm, 6.3–12.5 µm. Measured values are recorded in Fig. 2.

Application of anticorrosion protection

The technology of anticorrosion protection using paints is due to its simplicity often used not only in engineering praxis, but also other fields of industrial or agricultural production. The principle of this technology is to form a protective coating which isolates the metal subject from the environment. For the experiment, the following paints were chosen:

- water-thinnable paint "Eternal",
- synthetic coating composition "Hostagrund",
- duplex system – hot dipped zinc + "Zinorex".

In order to measure the passivating coating, a measuring probe Elcometr 456 standard was used. To achieve objective readings, each layer was represented by three samples. Out of each sample 5 readings were obtained and an arithmetic average, a standard deviation and a variation coefficient were calculated. The values of each reading as well as the mentioned statistical values are put in Tab. V.

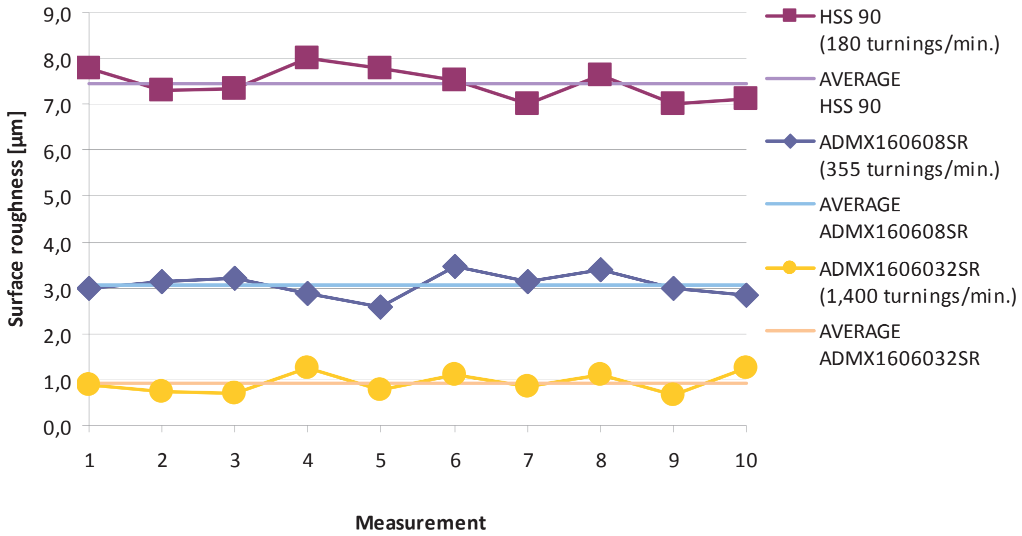
The individual systems were sprayed in two layers to the base material, the break between spraying the other coating was minimally 4 hours; temperature the environment was 22 °C.

Tearing test

In order to define the adhesion of anticorrosion system to the base material with different surface roughness, test according to ČSN EN ISO 4624 was used. This norm sets a procedure of tearing test on

IV: *Cutting conditions of cutting tools*

Cutting materials	Turnings [min^{-1}]	Shift		Depth of the cut [mm]	Cutting speed [m·min^{-1}]
		On tooth [mm·tooth]	On turning [mm]		
ADMX160608SR	355	0.046	0.280	1.0	70.226
ADMX1606032SR	1,400	0.012	0.071	1.0	276.948
HSS 90	180	0.018	0.220	0.5	35.607



2: *Surface roughness after cutting operation*

V: *Thickness of anticorrosion coatings of the individual systems*

Anticorrosion system	Thickness of anticorrosion coatings [µm]					Average [µm]	Standard deviation [µm]	Variation coefficient [%]
	1	2	3	4	5			
Eternal	87	83	80	88	85	84.60	2.87	3.39
Hostagrund	63	65	61	62	68	63.80	2.48	3.89
Hot dipped zinc + "Zinorex"	112	124	119	115	124	118.80	4.79	4.03

VI: *Adhesion values of the individual anticorrosion systems*

Anticorrosion system	Roughness range [µm]	Tearing power [MPa]					Average [MPa]	Standard deviation [MPa]
		1	2	3	4	5		
Eternal	0.4–1.6	0.40	0.50	0.50	0.30	0.50	0.44	0.08
	1.6–6.3	0.70	0.80	0.70	0.80	0.80	**0.76**	0.05
	6.3–12,5	0.60	0.90	0.90	0.60	0.70	0.74	0.14
Hostagrund	0.4–1.6	1.50	1.30	1.30	1.40	1.50	1.40	0.09
	1.6–6.3	1.90	2.10	2.10	2.00	2.00	**2.02**	0.07
	6.3–12.5	1.80	1.80	2.00	1.90	2.00	1.90	0.09
Hot dipped zinc + Zinorex	0.4–1.6	1.40	1.50	1.40	1.60	1.50	1.48	0.07
	1.6–6.3	1.60	1.50	1.40	1.50	1.60	**1.52**	0.07
	6.3–12.5	1.30	1.40	1.50	1.40	1.50	1.42	0.07

both single- and multilayer paint system. The result of this test is tensile stress needed to damage the weakest boundary (adhesion damage) or the weakest component (cohesion damage) of the tested set. Adhesion analysis of the individual anticorrosion systems was processed after the cutting operation.

Progress of preparation of testing samples:

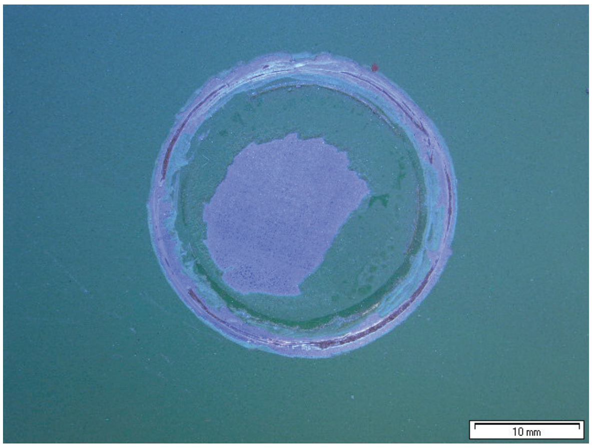
- cleaning using the degreasing agent perchlorethylen 99 %,
- application of a normalized testing detaching roller, diameter 20 mm,
- application of a two-component glue "Araldite",
- analysis of tearing power – tearer Elcometr (measurement range 0–7 MPa).

As it is apparent in Tab. VI, the highest adhesion values are reached by the anchoring profile in the interval of 1.6–6.3 µm. However, samples protected by the duplex system were damaged between the zinc coating and paint system.

Machined samples with surface roughness in the interval of 0.4–1.6 µm performed the lowest adhesion of water-thinnable paint "Eternal". The paint layer has completely been torn off from the base material in more than 50 % cases, see Fig. 3.

Corrosion degradation of the individual samples

Corrosion resistance of the individual protective systems was tested according to the norm ČSN



3: *Tear of testing detaching roller before corrosion test*

ISO 9227 – *Salt spray test (NSS method)*. Salt spray chamber Liebisch type S400M-TR was used for this experiment.

Testing parameters:

- temperature in the salt-spray chamber 35 ± 2 °C,
- concentration of the sodium chloride in a spraying medium 50 ± 5 g per l,
- pH value of the salt solution 6.5–7.2,
- the time interval was set for 10, 20 and 30 days. Based on an every-day visual evaluation and depending on the speed of corrosion degradation, the individual intervals may have differed.

In order to analyse the degradation of an anticorrosion system, tearing test according to the norm ČSN EN ISO 4624 was processed after each time interval.

Adhesion test of anticorrosion systems after corrosion degradation in salt-spray environment

Adhesion of the individual anticorrosion systems was tested also after the exposition to the salt-spray environment. Tearing test was processed also under the conditions set in the norm ČSN EN ISO 4624, where the power needed to tear-off a testing detaching roller was measured. The individual results are recorded in Tabs. VII–IX.

As corrosion attacked samples of water-thinnable system Eternal to a large extend, further tearing tests were not processed anymore.

No matter what anchoring profile, it can be deduced that all samples are subject of degradation, as it is seen in Tabs. VII–IX.

Corrosion degradation of water-thinnable paint Eternal after exposition to salt-spray environment is depicted in Fig. 4, left. There is well visible undercorrosion to the base material.

Delamination of acrylate system "Zinorex" applied to the zinc-dipped coating appeared always in the layer between the two protective layers, see Fig. 4, right. Duplex systems are characterized by a long service life, but there is a risk of peel-off the top anticorrosion coating (Votava, 2011).

Undercorrosion of anticorrosion system according to the norm ISO 4628-8

The test is focused on observation of undercorrosion of the protective system, in which is artificially made a cut (that is defect) to a base material. This test was processed to observe the corrosion process under the anticorrosion system. The main evaluation criterion of corrosion resistance in different surface is roughness of tested samples.

VII: *Adhesion test after a 10-day salt-spray test*

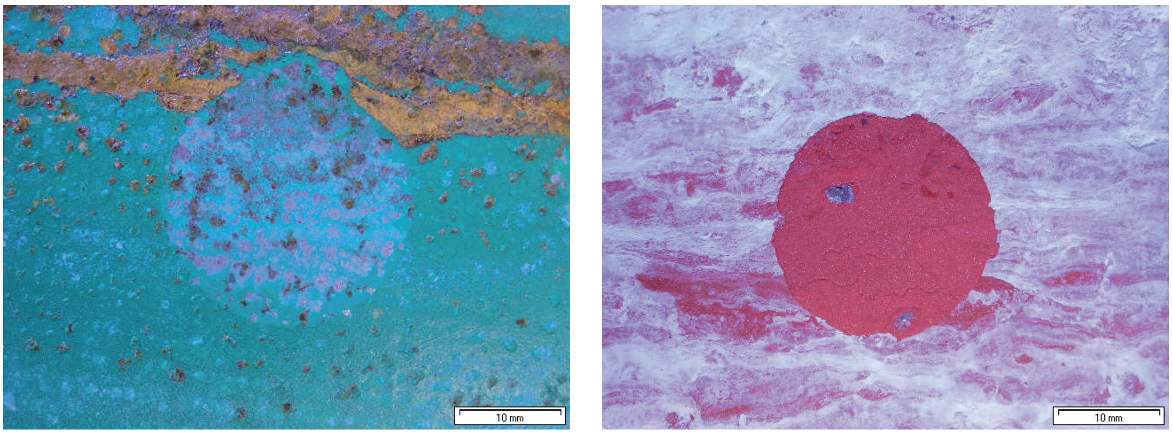
Anticorrosion system	Roughness range [μm]	Tearing power [MPa]					Average [MPa]	Standard deviation [MPa]
		1	2	3	4	5		
Eternal	0.4–1.6	0.30	0.30	0.40	0.30	0.30	0.32	0.04
	1.6–6.3	0.50	0.60	0.50	0.70	0.60	**0.58**	0.07
	6.3–12,5	0.50	0.40	0.50	0.30	0.50	0.44	0.08
Hostagrund	0.4–1.6	1.60	1.60	1.40	1.60	1.40	1.52	0.10
	1.6–6.3	1.70	1.90	1.90	1.80	1.70	**1.80**	0.09
	6.3–12.5	1.90	1.80	1.80	1.70	1.80	**1.80**	0.06
Hot dipped zinc + Zinorex	0.4–1.6	1.30	1.30	1.30	1.50	1.30	1.34	0.08
	1.6–6.3	1.40	1.30	1.60	1.80	1.30	**1.48**	0.19
	6.3–12.5	1.50	1.30	1.60	1.20	1.50	1.42	0.15

VIII: *Adhesion test after a 20-day salt-spray test*

Anticorrosion system	Roughness range [µm]	Tearing power [MPa]					Average [MPa]	Standard deviation [MPa]
		1	2	3	4	5		
Eternal	0.4–1.6	–	–	–	–	–	–	–
	1.6–6.3	–	–	–	–	–	–	–
	6.3–12,5	–	–	–	–	–	–	–
Hostagrund	0.4–1.6	1.30	1.20	1.30	1.10	1.10	1.20	0.09
	1.6–6.3	1.40	1.40	1.40	1.20	1.30	1.34	0.08
	6.3–12.5	1.40	1.50	1.50	1.40	1.50	**1.46**	0.05
Hot dipped zinc + Zinorex	0.4–1.6	1.20	1.20	1.30	1.20	1.30	1.24	0.05
	1.6–6.3	1.20	1.30	1.30	1.40	1.10	**1.26**	0.10
	6.3–12.5	1.10	1.20	1.10	1.30	1.10	1.16	0.08

IX: *Adhesion test after a 30-day salt-spray test*

Anticorrosion system	Roughness range [µm]	Tearing power [MPa]					Average [MPa]	Standard deviation [MPa]
		1	2	3	4	5		
Eternal	0.4–1.6	–	–	–	–	–	–	–
	1.6–6.3	–	–	–	–	–	–	–
	6.3–12,5	–	–	–	–	–	–	–
Hostagrund	0.4–1.6	0.80	0.70	0.70	0.60	0.70	0.70	0.06
	1.6–6.3	0.90	0.80	0.80	1.00	0.90	**0.88**	0.07
	6.3–12.5	0.80	0.80	0.60	0.60	0.70	0.70	0.09
Hot dipped zinc + Zinorex	0.4–1.6	0.90	1.10	1.00	1.00	1.10	**1.02**	0.07
	1.6–6.3	1.00	1.10	1.00	0.90	0.90	0.98	0.07
	6.3–12.5	0.90	0.90	1.00	0.80	1.10	0.94	0.10



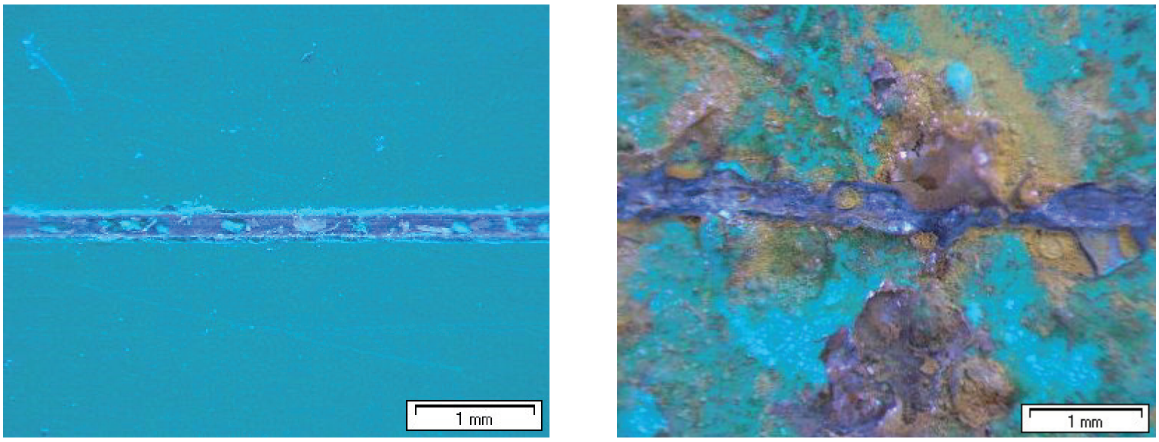
4: *Tear-off a testing detaching roller, water-thinnable paint Eternal after a 10-day salt-spray test (left), duplex system after a 30-day salt-spray test (right)*

Following the procedure described in the norm ISO 4628-8, there was made an independent cut in the "I" shape, whose depth was up to the base material. This method is appropriate for corrosion tests where paint system up to 500 µm was applied. Further, the samples were placed to the corrosion environment. During the exposition to the salt spray environment, the following changes were observed:

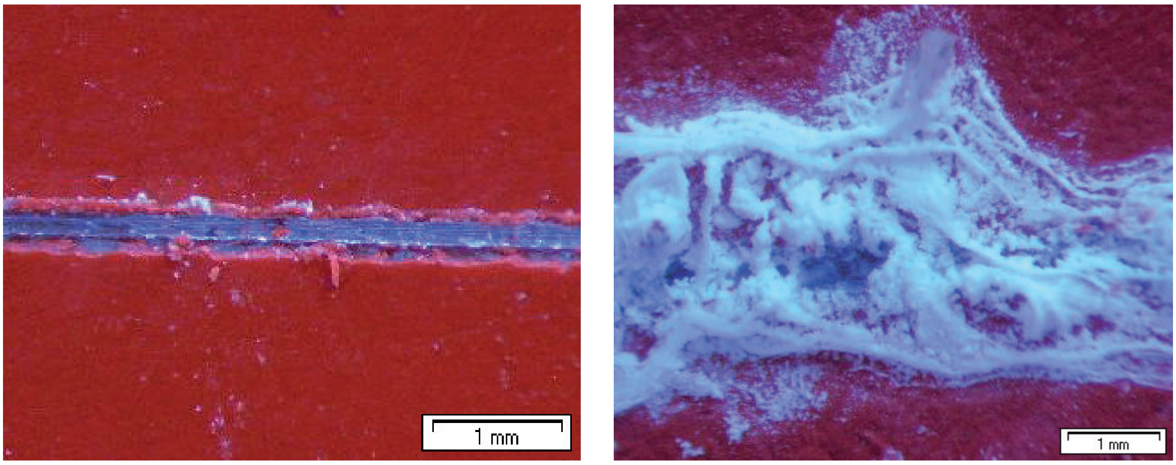
- visual control of damage of anticorrosion system in the area of cut,
- analysis of blebs near the cut.

As it is apparent from Fig. 5, the water-thinnable paint Eternal was not able to resist the corrosion environment. There was described a full-area undercorrosion no matter where the testing cut was made. This result can be stated no matter what was the roughness of the anchoring profile.

In the salt-spray environment, anticorrosion zinc-based systems form zinc hydroxide, which covers equally the whole surface of a sample (Votava, 2012). This thesis was confirmed also in this experiment, where the cut was clogged by zinc hydroxide, which



5: *Undercorrosion of water-thinnable paint Eternal, surface roughness 3 μm: before the corrosion test (left), after 10-day exposition to the salt-spray environment (right)*



6: *Undercorrosion of the Zinorex system: before the corrosion test (left), after 10-day exposition to the salt-spray environment (right)*

formed a passivating layer of the defected spot, see Fig. 6. The influence of surface roughness treated by Zinorex on undercorrosion of the anticorrosion system cannot be evaluated.

CONCLUSION

This paper analyses adhesion of three different anticorrosion systems, which were applied on samples of different roughness of machined surface. The base material for application of any anticorrosion system was steel C45E. In order to increase the machining performance and hardness, the steel had been heat treated (normalized) before application of any protective coating.

Machining was processed on a vertical knee and column type of milling machine using different cutting tools and different cutting speeds, which achieved 3 different intervals of surface roughness: 0.4–1.6 μm, 1.6–6.3 μm and 6.3–12.5 μm. Further, three different anticorrosion systems were applied on the samples: water-thinnable paint "Eternal", synthetic paint "Hostagrund" and duplex system consisting of hot-dipped zinc + acrylate paint "Zinorex".

In order to analyse the adhesion performance of the individual systems, tearing test in compliance with the norm ČSN EN ISO 4624 was processed. Also samples tested in salt-spray environment according to the norm ČSN EN ISO 9227 underwent the tearing test. The dependence of surface roughness on adhesion of anticorrosion system was proved.

Anchoring profile in the roughness interval of 0.4–1.6 μm always performed the lowest power needed to tear-off the testing detaching roller. Duplex system showed delamination between the paint and the zinc coating. From the measured values it can be stated that the adhesion of zinc coating to the base material is higher than 1.6 MPa.

No matter what corrosion system, the longer the corrosion tests were, the less corrosion resistant the anticorrosion systems were. The water-thinnable paint showed such a low corrosion resistance that after a 10-day corrosion test that these samples were not subject to further testing. Readings from the individual tests are recorded in Tabs. VII–IX.

The paper analysed the relation between roughness of machined surface and the ability of various anticorrosion protections to form a protective layer with a sufficient adhesion. Based on the particular results, there was proved the optimal roughness value in the interval of 1.6–6.3 µm, where the average roughness value Ra was 3.07 µm. However, it has to be noticed, that this paper brings only a partial evaluation of anticorrosion protections; in order to generalize the results a further and deeper research has to be processed.

SUMMARY

Quality anchoring profile is a basic condition for any anticorrosion protection. The quality is defined by the roughness of the surface which originated in the following processes, such as machining, casting, forging etc. These remains after machining tools or sand mould affect crucially the anticorrosion protection.

The scientific literature brings a wide interval of surface roughness depending on application of various anticorrosion protections. Even for anticorrosion protection by zinc hot-dipping, there is recommended a higher roughness than when applying on metallurgical steel components.

The paper is focused on a real evaluation of adhesion of anticorrosion system depending on a certain surface (anchoring profile). The analysis also covers degradation of anticorrosion systems under the conditions of salt-spray environment. The evaluation criterion of adhesion of the individual anticorrosion systems is the power needed to tear-off a testing detaching roller from tested samples. The tearing test was processed under the conditions set in the norm ČSN EN ISO 4624 and the analysis of undercorrosion in compliance with the norm ISO 4628-8. According to the results of undercorrosion test, the dependence of surface roughness on undercorrosion of the individual anticorrosion systems was not proved.

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