Effects of Surface Preparation Methods on Adhesion of Organic Coatings to Steel Substrates

A number of parameters affect the adhesion of coatings to steel substrates. According to ISO 8503, these conditions include the following substrate properties:

• rust and mill scale;
• contaminants, such as dust, oil, grease, and salts; and
• profile (roughness).

In turn, the conditions above influence the selection of a method to prepare the substrate for coating application. Several studies have evaluated the effects of surface preparation methods, primarily dry abrasive blasting (AB) and waterjetting (UHP), on coating performance. These studies also investigated the long-term behaviour of coating systems. These studies, however, focused on the effects of flash rust and salt contamination. Combining AB and UHP (UHPA B) into a single blasting process is an innovative approach to surface preparation. Although this method has already been introduced into ship repair practice, there is not enough information available to evaluate the quality of surfaces and coating adhesion associated with UHPA B. This study’s goal is to systematically investigate parameters that are suitable for evaluating the quality of a steel substrate after the use of three surface preparation methods: AB, UHP, and UHPA B. The investigation focuses on repair of ships and steel structures. The selected coating systems were mainly suitable for ballast tank applications. However, one coating, originally designed for steel structures in water, such as weirs and flood barrages, was also included to check the capabilities of the investigated methods to prepare such surfaces.

The exposure environment for the coatings to be studied was selected according to the classifications...
Surface preparation and coating application were excellent because they were performed under ideal, controlled conditions. Such conditions cannot be expected in field work.

### Surface Preparation and Coating Procedures

Three methods were used for surface preparation:

- A B as shown in Fig. 1a;
- UHP as shown in Fig. 1b; and
- UHPAB as shown in Fig. 1c.

The performance parameters of these methods are listed in Table 2. The abrasive used for A B and UHPAB was a commercial copper slag with the following properties in accordance with ISO 11126-3:6:

- hardness > 7 (Mohs);
- density = 3600 kg/ m³;
- particle size range = 0.4–1.2 mm; and
- particle shape—irregular.

For the UHP and UHPAB applications, tap water with an electrical conductivity of 400 and 800 µm (16 and 32 mils). After coating removal, the surfaces treated with UHP and UHPAB were allowed to dry (Fig. 2). After the coatings cured, adhesion tests were performed as described below.

Five commercially available epoxy coating systems were selected. Their major properties are listed in Table 3. The coatings were applied by airless spray in a paint booth with a controlled climate. The coatings cured for 50 days. Then, specimens for the laboratory tests were manufactured. Each was 15 cm x 10 cm (6 in. x 4 in.) according to the requirements of ISO.
The specimens were cut with plate shears. Commercially available coatings were manually applied to each sample for edge protection. One sample of the plates prepared with A B and UHPAB was not coated, but was saved for scanning electron microscopy (SEM) inspections. From these samples, small specimens with the dimensions 20 mm x 20 mm (~1 in. x 1 in.) were cut.

Roughness was measured according to ISO 8503-4 using a portable stylus instrument. Adhesion between the coating and the substrate was estimated according to ISO 4624, by means of a commercial pull-off testing device.

**Table 3: Properties of Applied Coating Systems**

<table>
<thead>
<tr>
<th>Property</th>
<th>Coating System</th>
<th>1a</th>
<th>1b</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primer</td>
<td>Zn</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Number of coatings</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Density in kg/l</td>
<td>2.8</td>
<td>1.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Solid content in vol.-%</td>
<td>67</td>
<td>100</td>
<td>96</td>
<td>83</td>
<td>60</td>
<td>80</td>
<td>—</td>
</tr>
<tr>
<td>DFT in µm</td>
<td>70</td>
<td>490</td>
<td>346</td>
<td>253</td>
<td>273</td>
<td>374</td>
<td></td>
</tr>
<tr>
<td>VOC in g/l</td>
<td>—</td>
<td>—</td>
<td>free</td>
<td>—</td>
<td>385</td>
<td>170</td>
<td></td>
</tr>
</tbody>
</table>
with a maximum load capacity of 18 MPa. The dollies were stainless steel, 20 mm (~1 in.) in diameter. The drying time for the glue was four hours. The samples were pre-cut before the pull-off tests were performed. Six measurements were taken for each sample. Because three samples were available for testing, 18 measurements were taken for each condition. The portion of adhesive failure and cohesive failure was evaluated from the appearance of the failed sections.

Results and Discussion
The results of the roughness measurements are summarized in Fig. 3. For substrate evaluation, the roughness parameter “average maximum roughness,” $R_{YS}$, in accordance with ISO 5803, is very often specified. This parameter is equal to the roughness parameter $R_Z$ measured with the stylus. This parameter has high values for the UHPAB surfaces, followed by the AB surfaces and the UHP surfaces. The same trend is true for the average roughness $R_A$. The maximum roughness, $R_{max}$, however, shows a somewhat different trend. Here, AB forms the deepest profile, followed by UHPAB and UHP. But the differences in the maximum roughness between UHPAB and AB are only 3%. It seems from these results that UHP does not have the capability to form a new profile under the conditions of this study.

The results of the pull-off tests are summarised in Figs. 4 and 5. In Fig. 4, two groups of columns can be distinguished. The first group covers coating systems 1, 3, and 4, whereas the second group covers coating systems 2 and 5. The first group is characterised by two features. First, the pull-off failure was always cohesive (within the coating), not adhesive (between the substrate and the coating). Second, the individual coating systems showed a more or less constant level of pull-off strength val-
Table 4: Grit Contamination of Substrates after AB

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Contamination in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (AB)</td>
<td>27.7</td>
</tr>
<tr>
<td>2 (AB)</td>
<td>60.9</td>
</tr>
<tr>
<td>3 (AB)</td>
<td>49.4</td>
</tr>
<tr>
<td>4 (AB)</td>
<td>54.1</td>
</tr>
<tr>
<td>5 (AB)</td>
<td>68.9</td>
</tr>
</tbody>
</table>

Fig. 6: Type i grit contamination after AB (dry abrasive blast cleaning)

Fig. 7: Effects of surface preparation methods on type ii grit contamination a, b – after AB (dry abrasive blast cleaning); c, d – after UHPAB (ultra-high pressure abrasive blasting)

...
the trends in roughness and pull-off strength were different. Samples with high roughness values (such as samples prepared with AB) do not show the highest values for pull-off strength.

**Surface Contamination**

To understand the rather unexpectedly low adhesion capacities of the AB substrates, we performed SEM inspections of the blasted surfaces. Embedded grit particles are common on grit-blasted surfaces. Similar to dust, the particles may act as separators between the substrate and the coating system. In studies of particle embedment during grit-blasting, experimental results have shown that grit embedment depended mainly on impact angle and abrasive type. Investigations by Fairfull and Weldon showed a notable effect of grit type and morphology on contamination. Slag material (except nickel slag) was very sensitive to grit embedment. Experiments with copper slag showed that the breakdown behaviour of individual particles during the impingement at the steel surface seemed to play an important role. It was apparent that the embedment was not simply due to discrete particles lodging in the substrate, but rather to extreme breakdown of the slag abrasive into minute particles, or a physical smearing of the grit over the surface. Embedded grit reduces the adhesion of the coating to the substrate. Measurements of the adhesion strength as a function of the amount of embedded grit were performed by Griffith et al. These authors showed that adhesion strength diminished significantly if grit particles were embedded in the substrate surface. However, we observed the following two types of grit contamination.

- **Type i**: mechanical embedment of rather large abrasive particles (Fig. 6)
- **Type ii**: adhesive smearing of very finely grained grit particles over the surface (Fig. 7)

Note the high amount of contamination in Figs. 7a and 7b. Imaging software was used to estimate the percentage of grit contamination. The results of the measurements performed on the substrates prepared with AB are listed in Table 4. Contamination levels are between 27.7 and 68.9%. A ISO of interest is the type of contamination. The images clearly show a layer of finely ground particles that cover the substrate surface similar to a separation layer. This layer prevents direct contact between the coating and the substrate. The degree of contamination is notably lower for UHPAB (Figs. 7c and 7d). This is probably due to the cleaning capability of the high-pressure water flow that is part of the UHPAB system. Figure 8 shows an SEM image taken from the polished cross section of a coated AB substrate. Considerable accumulations of debris can be noted between the substrate and coating at places. The debris were identified by EDX analysis to be copper slag.

We concluded from these observations that smearing of crushed abrasive particles over the substrate surface is a probable reason for the poor performance of the organic coating systems 2 and 5 on substrates prepared by AB. This behaviour has some counterpart if flash rust intensity is evaluated. Coating manufacturer specifications do not allow the coating of substrates showing heavy flash rust (designation H), whereas light (L) and even moderate (M) flash rust can be tolerated sometimes. The reason for this restriction is mainly that heavy flash rust does not adhere strongly enough to the substrate.

However, because some coatings in our study are not affected by grit contamination, one could assume there are...
other causes of the difference in adhesion. The question arises of whether some types of coatings are compatible with grit-contaminated surfaces. Such coatings could be analogous to those defined as flash rust-tolerant coatings. The capability of the liquid coating to penetrate the grit layer and to encapsulate individual grit particles may play a notable role. A similar process was reported by Kaiser and Schütz\textsuperscript{13} with regard to rust. A programme is planned to investigate this issue. For coating systems 2 and 5, the UHP samples show slightly lower adhesion values than the UHPAB samples. These discrepancies could be explained by the lower roughness of the substrates prepared with UHP. Although UHP samples are completely clean in terms of grit contamination, their profile is too low to contribute to better adhesion.

A nother conclusion from our study is that the assessment of dust on steel surfaces according to ISO 8502-3\textsuperscript{14} is not sufficient because it considers only dust particles visible under 10x magnification. The microscopically small abrasive debris found in our study cannot be detected by this method. Therefore, even substrates that are categorised as dust size class “0” in ISO 8502-3\textsuperscript{14} may not be completely free of dust contamination.

**Summary**

The investigation shows that a sensitive balance exists between surface preparation method and the coating system to be applied. A proper combination of both can notably improve adhesion and corrosion resistance in general because good adhesion is a precondition for good performance of protective coating systems. A layer of microscopic, finely crushed abrasive particles embedded in the surface seems to affect bonding between the substrate and coating for some coating systems, while for others it does not. With UHP and UHPAB, this effect can be eliminated, and an optimum surface morphology can be achieved with UHPAB. Salt spray test results for the performance of the coating systems and substrates discussed in this article will be reported later.

**References**

1. ISO 8503: Preparation of Steel Substrates before Application of Paints and Related Products.