Application of MIPAR Software in the Quantitative Analysis of Corroded Surfaces

Primena MIPAR softvera u kvantitativnoj analizi korodirane površine

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https://doi.org/10.65614/uisk_yucorr.2025.26.ch28

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Abstract

Corrosion is a common failure mechanism in steel and its structural components, often compromising their mechanical integrity and service life. One widely used method of protection is the application of functional coatings (organic, inorganic, or hybrid) that are tailored to perform specific roles under various environmental conditions. This study investigates the use of MIPAR, a powerful image analysis software, in the quantitative evaluation of corroded surfaces to assess the performance of such coatings. Composite coatings were prepared by incorporating 5 wt.% of polyaniline into a commercial alkyd-based paint and applied onto carbon steel substrates. The polyaniline emeraldine salt was synthesized following the IUPAC-recommended procedure, involving deprotonation with ammonium hydroxide and subsequent reprotonation with sulfamic, succinic, citric, and acetic acids. The base coating and four composite coatings were then exposed to a corrosive environment (3% NaCl solution), and surface degradation was monitored through digital imaging. MIPAR analysis was employed to quantify surface corrosion coverage, enabling a detailed evaluation of coating performance and corrosion progression. This approach demonstrates how digital image analysis enhances the accuracy and efficiency of corrosion studies by providing measurable, reproducible data on coating performance. The results highlight the potential of integrating digital imaging and advanced software tools like MIPAR in the development of next-generation functional coatings, including those with self-healing properties. Furthermore, future applications of MIPAR may involve leveraging its machine learning capabilities and multi-layer imaging to analyze complex coating systems, corroded and healed surfaces. This integration can significantly streamline research workflows and accelerate the discovery of more effective corrosion protection technologies.

Keywords: *corrosion; image software; surface analysis; MIPAR*

Izvod

Korozija je čest mehanizam degradacije kod čelika i čeličnih konstrukcija, što značajno utiče na njihov mehanički integritet i radni vek. Jedna od najčešće korišćenih metoda zaštite jeste primena funkcionalnih prevlaka (organskih, neorganskih ili hibridnih) koje se mogu prilagoditi da obavljaju određene funkcije u različitim uslovima radne sredine. Ova studija istražuje upotrebu softvera MIPAR, efikasnog alata za analizu digitalnih slika, u kvantitativnoj evaluaciji korozije i efikasnosti zaštitnih prevlaka. Kompozitne prevlake su pripremljene dodatkom 5% polianilina u komercijalnu alkidnu boju i nanete su na podloge od ugljeničnog čelika. Polianilin smaragdna so je sintetizovana prema IUPAC-ovoj proceduri, koja podrazumeva deprotonaciju sa amonijum hidroksidom, a zatim reprotonaciju sa sulfaminskom, sukcinskom, limunskom i sirćetnom kiselinom. Bazni premaz i četiri kompozitna premaza su zatim izloženi korozivnoj sredini (3% rastvor NaCl), a degradacija površine je praćena digitalnim snimanjem. Za kvantifikaciju korodirane površine korišćena je MIPAR analiza,

što je omogućilo detaljnu evaluaciju performansi premaza i napredovanja korozije. Ovakav pristup pokazuje kako digitalna analiza slika može unaprediti preciznost i efikasnost istraživanja u oblasti korozione zaštite, pružajući merljive i ponovljive rezultate. Rezultati ukazuju na veliki potencijal integracije digitalnog snimanja i naprednih softverskih alata poput MIPAR-a u razvoju novih generacija funkcionalnih prevlaka, uključujući samopopravljajuće prevlake. Dodatno, buduća primena softvera MIPAR mogla bi obuhvatiti upotrebu njegovih naprednih mogućnosti u oblasti mašinskog učenja i višeslojne analize slika za detaljno ispitivanje kompleksnih prevlaka, korodirane i regenerisane površine. Ova integracija može značajno ubrzati istraživačke procese i doprineti razvoju efikasnijih tehnologija zaštite od korozije.
Ključne reči: *korozija; program za obradu slika; analiza površine; MIPAR*

Introduction

Corrosion is a pervasive failure mechanism in steel structures, causing significant economic losses and compromising structural integrity [1]. Localized forms, such as pitting and crevice corrosion, are particularly difficult to predict due to their dependence on environmental and material factors [2]. The consequences of corrosion are not only financial but can also threaten safety and reduce the service life of critical infrastructure.

Functional and smart coatings, including polyaniline-based systems, are widely used to protect metals by enhancing surface stability and delaying corrosion propagation [3]. These coatings can be tailored to provide multiple functionalities, such as barrier protection, hydrophobicity, or self-healing capability, depending on the application. Evaluating their performance requires reliable and quantitative assessment methods that go beyond traditional visual inspection, which is often subjective and time-consuming [4].

Digital imaging combined with automated analysis offers a powerful approach for such evaluations. MIPAR software enables the creation of automated analysis “recipes” to segment and quantify corroded surfaces efficiently, reducing manual effort while maintaining precision [5]. By integrating high-resolution imaging with computational analysis, MIPAR allows researchers to track corrosion progression, compare coating performance, and support the development of more effective protection strategies.

Material and Methods

As already described in our previously published paper, polyaniline in a powdered form was produced using the chemical synthesis route [6, 7]. Composite coatings were prepared by incorporating 5 wt.% of polyaniline into a commercial alkyd-based paint and applied onto carbon steel substrates. The polyaniline (PANI) emeraldine salt was synthesized following the IUPAC-recommended procedure [8], involving deprotonation with ammonium hydroxide and subsequent reprotonation with sulfamic, succinic, citric, and acetic acids. The base coating and four composite coatings were then exposed to a corrosive environment (3% NaCl solution). The image of surfaces of the samples was made using a PANASONIC DC-FZ82 digital camera (Panasonic Corporation, Kadoma, Osaka, Japan). A digital image analysis using MIPAR v.4.50 (MIPAR Image Analysis, Columbus, Ohio, USA) was employed to quantify surface corrosion coverage, enabling a detailed evaluation of coating performance and corrosion progression [9].

The method of selecting the pixels that correspond to the corroded surface was within the specified hue, saturation, and pixel value ranges according to the settings presented in figure 1.

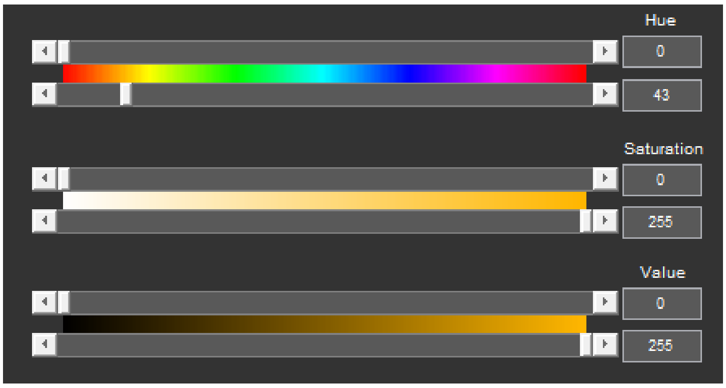

Figure 1. *Illustration of the settings of selecting colors from the image [10].*

The selection of pixels was performed by eyedropper function, additively expanding the range of hue, saturation, and value. Six recipes were developed using the color selection feature, five were tailored to their respective images for the tested samples, while one was developed to be used on all five corroded images. The overarching recipe used for all the images was modified to exclude the dark and gray areas at the corner of the images as well as the marked numbers. All the color selection data for the recipes are given in table 1.

Table 1. Color selection ranges for the recipes used on the images of corroded surfaces

Recipe	**Hue**		**Saturation**		**Pixel value**	
I	17	48	12	161	123	255
II	0	65	3	255	74	255
III	17	49	13	255	100	255
IV	0	48	33	255	83	255
V	0	360	22	255	56	255
All*	0	360	12	255	66	255

*modified to exclude gray and black surfaces

Results and Discussion

The surface area of the tested samples was measured to be 11.074 cm^2 and the non-corroded sample coated with the composite of polyaniline and sulfamic acid is shown in figure 2. The polyaniline particles are visible as black dots while the improper dispersion could be seen as a bluish hue. By use of MIPAR software, the particles were highlighted in pink and the unapplied or uneven coating in green, while the product of the overarching recipe on the non-corroded surface is given in red.

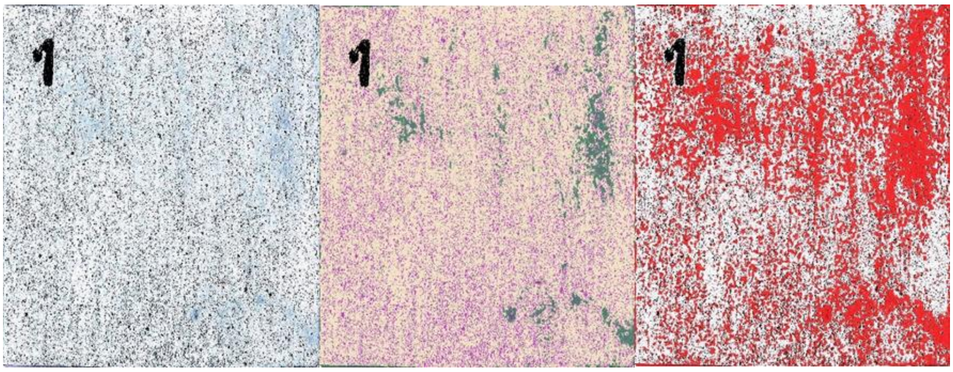

Figure 2. *Non-corroded sample (left), MIPAR selection of particles and coating (middle), result of recipe „All" on non-corroded sample (left).*

The main difficulty when applying the same recipe on the corroded surfaces stems from their differences in brightness, contrast, and exposure when the photos were taken. In order to uniformly identify the intensity of the corrosion on the tested surface it is crucial to keep the changes in these settings to a minimum when acquiring the photographs. If that is unavoidable, it is recommended to take a reference photo of a non-corroded sample under the same conditions. The differences in these settings in the original images are seen in their image pixel histograms (figure 3). These can be altered by utilizing the pre-processing functions like *Flatten Background* or *Histogram equalization* and *Smart Clusters;* however, these are not recommended since the dark coating particles can be confused with the corroded surfaces, thus *Color Selection* was the only function employed.

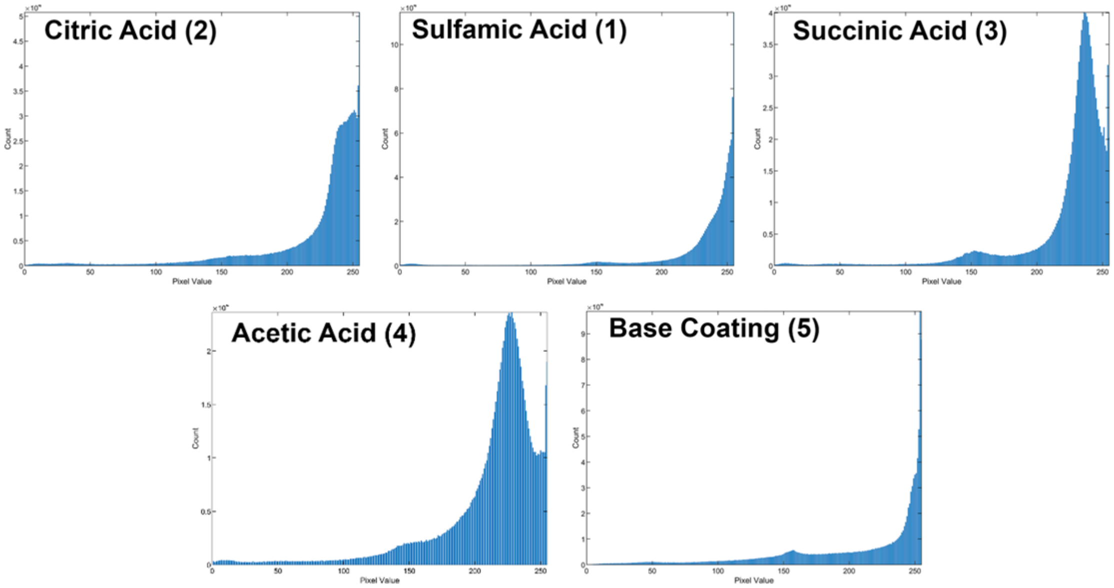

Figure 3. *Image pixel histograms of original image.*

The peak in pixels values between 120 and 180, or more specifically the peak from 150 to 160, corresponds to both the gray areas at the edge of the samples as well as the mild brown rusted corroded surface, that can be seen across all the coated samples in figure 3.

The results of each corroded surface for every recipe are presented in table 2 as percentage of the covered surface within the whole image. The lower the value the more efficient the composite coating is, making the best composite coating those of polyaniline doped with sulfamic acid, and succinic acid to a lesser extent. Among all samples, the base polyaniline coating exhibited the lowest performance. We can observe how the differences in recipe approaches are reflected on the results of area measurements.

Table 2. Percentages of the corroded surface area measured by different recipes

Coating type (Sample No.)	**Recipe**					
	I	**II**	**III**	**IV**	**V**	**All**
Sulfamic Acid (1)	**9.59**	27.53	0.005	1.67	4.43	11.17
Citric Acid (2)	15.79	**24.62**	16.09	13.73	17.27	20.94
Succinic Acid (3)	11.06	22.01	**10.90**	4.82	8.57	13.29
Acetic Acid (4)	28.93	58.13	28.76	**19.32**	24.45	31.18
Base Coating (5)	51.11	83.34	52.65	47.00	**58.18**	68.77

The values for the tailored recipes on their respective sample surfaces, as well as the overarching recipe next to the original images, are shown in figure 4. The most significant discrepancy between the tailored and the overarching recipe results was observed for the composite with acetic acid (11.86 %), while the minimal difference was observed for the least corroded sample with sulfamic acid composite (1.58%).

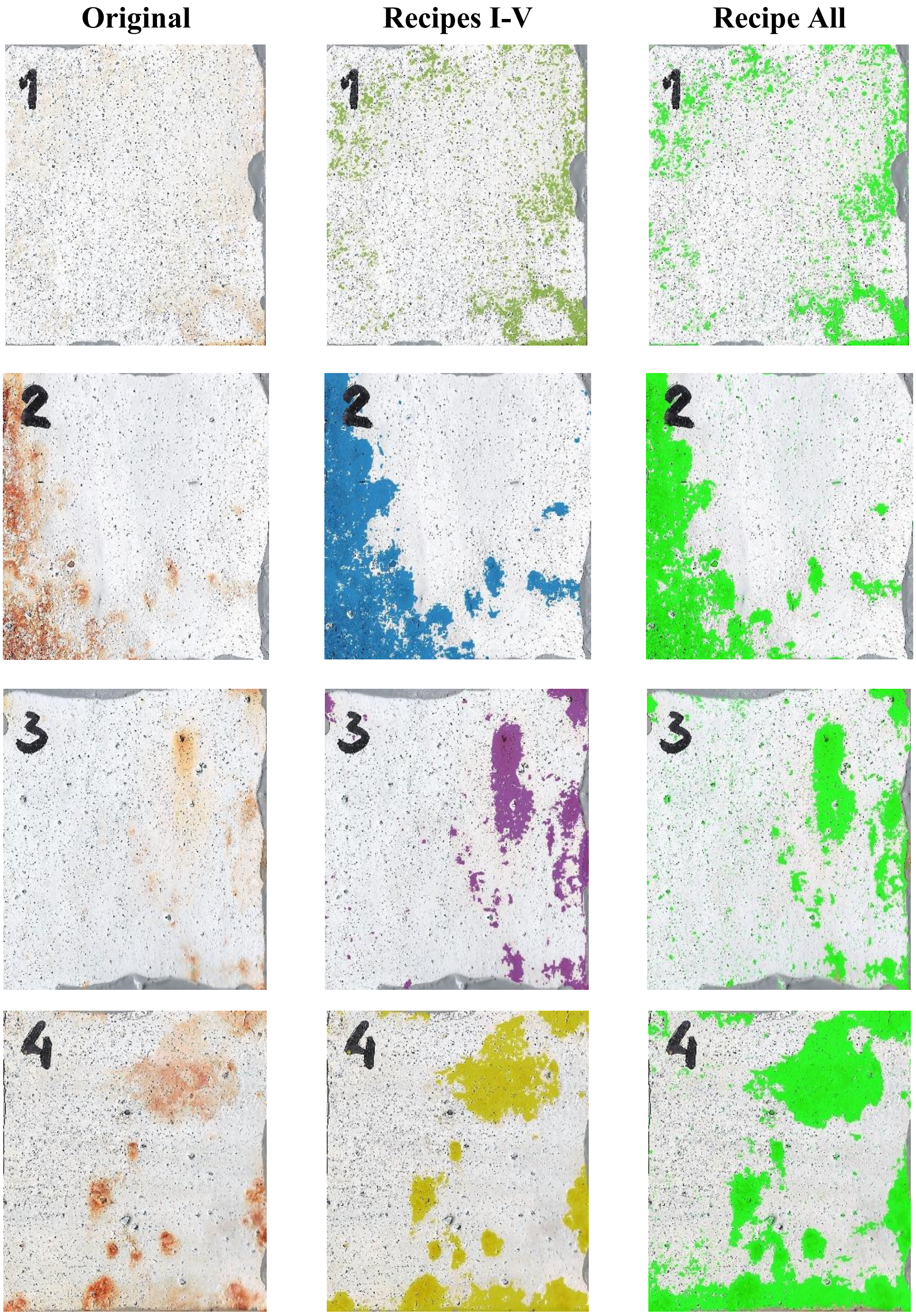

Figure 4. *Results of MIPAR analysis with reference images: original corroded surface (left), recipes tailored for each image (middle), overarching recipe (right).*

Combining the percentages of the corroded areas from respective recipes with the total image surface of 11.074 cm^2, the corroded area for each sample is obtained (table 3). Furthermore, assuming that the tailored recipes are more accurate and representative, in comparison to the overarching recipe, the absolute error can be calculated. The average absolute error (E_{abs}) is 0.553 cm^2, which is equal to 4.99 % of the total image surface.

Table 3. Recalculated corroded surface area (in cm^2) of the coated samples

Recipe	**Sample No.**				
	1	**2**	**3**	**4**	**5**
I-V	1.062	2.727	1.207	2.707	6.443
All	1.237	2.319	1.472	3.453	7.615
E_{abs}	0.175	0.408	0.265	0.746	1.172

In order to improve the applicability of MIPAR and to create an overarching recipe that can accurately estimate the corroded area on various samples, a much larger sample set should be studied. Moreover, the *Color Selection* function can be used to correlate the pixel color with the degree of corrosion on the studied surfaces. However, for the purpose of this paper, the software's capabilities proved to be quite appropriate.

Conclusion

Overall, the use of software programs for digital image analysis, such as MIPAR, has shown to be accurate and reliable in order to estimate the corroded surface area. However, in order to make a recipe that can work uniformly and that can identify the intensity of the corrosion on the tested surface, it is crucial to establish a minimal set of sample images to train the recipe. On the other hand, it is also helpful to avoid changes in brightness, contrast, and exposure between the images as much as possible. In this instance, five recipes were developed for their respective images and one recipe was developed to work on all five images. If we take the tailored recipes as representative, than the overarching recipe has an average absolute error of 0.553 cm^2, which is equal to 4,99 % of the total image surface. In the future applications, MIPAR can be employed to analyze the efficiency of coating application on the sample surface. The uniformity of the coating before the corrosion process can be compared to the distribution of the corroded areas, so their overlap can be quantified. However, in order to successfully employ MIPAR software, the coated samples need to have a small area of pristine surfaces. In summary, MIPAR is a versatile software program with multiple tools for image analysis, which can be utilized in various manners in order to better understand and evaluate the corrosion process.

Acknowledgements

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-136/2025-03/200023 and 451-03-136/2025-03/200135).

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