OBSERVATION OF TECHNOLOGICAL PARAMETERS INFLUENCING MECHANICAL PROPERTIES AND CRACK DEVELOPMENT IN ALUMINIUM COMPONENTS POST-CATAPHORETIC COATING

PATRIK FEJKO[1], DAMIAN PETI[1], MIROSLAV GOMBAR[2], JOZEF DOBRANSKY[1], OLHA, KALMAN[1], ĽUBOSLAV STRAKA[1]

[1]Technical University of Kosice, Faculty of Manufacturing Technologies with a seat in Presov, Sturova 31, 080 01 Presov, Slovak Republic

[2]University of West Bohemia Pilsen, Faculty of Mechanical Engineering, Univerzitni 8, 306 14 Plzen, Czech Republic

DOI: 10.17973/MMSJ.2025_06_2025051

patrikfejko@tuke.sk

The article under consideration pertains to the study of the influence of selected process factors of surface pretreatment on the quality of cataphoresis coating. The present study is focused on the evaluation of the length of cracks formed during mechanical stress (i.e., the bending test), which serve as an indicator of the adhesion and integrity of the formed coating. The present study investigates three primary factors that influence the degreasing process: the initial concentration of the degreasing solution (k_{ODM}), the deposition time (t_{ODM}), and the temperature of the degreasing process (T_{ODM}). Two types of degreasing solutions were utilized for experimental validation, with each solution investigated separately in a large-scale planned experiment designed according to the principles of central composite design (CCD). The objective of this study is to examine the impact of these parameters on the formation of cracks in the cataphoresis coating and to elucidate potential correlations between the quality of the surface treatment and the parameters of the degreasing process. The experimental findings revealed that variations in crack lengths, ranging from 1 to 100 millimeters, were observed contingent upon the specific combination of factors that were examined. The ensuing results are presented in graphical outputs and a decision tree, which facilitate the identification of interactions between the factors. This study makes a significant contribution to the field by offering a more profound comprehension of the process influences on the mechanical properties of cataphoresis coatings. Furthermore, it provides insights that are valuable for optimizing the process flow in practice.

KEYWORDS

Cataphoretic coating, degreasing solution, crack length, surface preparation, process optimization, coating durability

1 INTRODUCTION

Surface treatment constitutes a pivotal component of the manufacturing process, exerting a substantial influence on the quality and durability of the final product. Consequently, it is imperative that this phase of production be executed with the utmost precision and meticulousness, as the long-term functionality and reliability of the material are contingent on the quality of its surface finish. The implementation of surface treatments serves a multifaceted purpose, encompassing the protection of materials from damage and weathering, as well as the enhancement of adhesion [Flores 2011], [Kirchgeorg, 2018]. Mechanical bending tests are essential for assessing the quality of cataphoresis coatings, verifying properties like adhesion, flexibility, and resistance to mechanical stress. They simulate real operating conditions where deformation may damage the coating [Brown 2016]. In the bending test, the sample is bent around a defined radius to assess coating adhesion and integrity. The surface is then inspected for cracks, delamination, or flaking—especially important for aluminum, which deforms more easily. This quick and effective test is key for evaluating the elasticity and mechanical resistance of cataphoretic coatings, especially on components exposed to dynamic loads in automotive and aerospace applications [Oberreiter 2021]. Fejko [Fejko 2024] conducted a key study on crack length in cataphoretic coatings, using 88 CR4 and CR5 steel samples and a DOE-based central composite design. The research focused on how degreasing solution concentration and immersion time affect crack formation during bending. It also examined variations in surface pretreatment steps, with results presented graphically. Fejko [Fejko 2024], in the study " *Monitoring of technological factors to change the length of the crack created by cataphoretic coating*," found that stress during electrophoresis significantly affects crack initiation and growth in coatings on steel parts. The research highlights the importance of precise control over process parameters to enhance coating quality and durability.

Proper adhesion is crucial, as poor bonding accelerates crack growth. Dobransky [2023] showed that in cathodic electrocoating (CEC) of aluminum, stress and deposition time significantly affect coating thickness. Optimal settings improve coating quality and reduce crack formation, especially under varying environmental conditions.

These studies address a wide range of parameters affecting coating properties. However, a thorough investigation of the effect of surface pretreatment, particularly degreasing parameters, on the mechanical integrity of cataphoresis coatings is lacking in the literature. In particular, the impact of degreasing solution concentration, temperature, and application time on crack initiation and coating damage has not been adequately explored, especially with regard to aluminum substrates commonly used in industry.

This study addresses this gap by evaluating the effect of different degreasing parameters on the quality of cataphoresis coatings applied to AW 1050 H24 aluminum. Using an experimental approach based on the design of experiments methodology and supported by graphical and statistical analyses, this research aims to identify the optimal degreasing conditions that minimize defect occurrence and enhance corrosion protection quality.

2 MATERIAL AND METHODS

Two approaches were utilized in the experiment: a traditional experimental design and a planned experiment. In the conventional experimental design, all possible combinations of input factors and their levels are systematically tested. While this approach enables a thorough examination of the effects, it is exceedingly time-consuming and therefore of limited practical utility. In a deliberate experiment, statistical methodologies (e.g., factorial designs) are employed to select the most suitable combinations of factors, representing a more contemporary approach. This approach has been demonstrated to reduce the number of experiments necessary, enhance the reliability of the results, optimize the control of experimental conditions, and facilitate more efficient data analysis and interpretation.

The meticulous execution of this experiment, guided by the principles of a systematic design, yielded enhanced measurement precision, a more comprehensive data analysis, and more precise conclusions. [Mason 2003]

Tables 2, 3, and 4 present the experimental design. Table 2 enumerates the controllable input factors associated with the degreasing process, while Tables 3 and 4 catalog the constant input factors for the cataphoresis painting and polymerization processes, respectively. This approach ensures that all pertinent parameters associated with the individual process steps are explicitly delineated.

2.1 *Material Selection*

The selection of the AW 1050A H24 aluminum alloy for this study was predicated on its high purity (99.5% aluminum), excellent corrosion resistance, and enhanced thermal and electrical conductivity. The material's high aluminum content offers distinct advantages, including enhanced formability and ease of processing, which are crucial for the efficient formation and rolling of the material. The mechanical and physical properties of aluminum are delineated in Table 1. The material is also readily available and economical. However, it is important to note that this alloy exhibits lower strength compared to other aluminum alloys, which limits its suitability for applications requiring high mechanical strength. The term "H24" is employed to denote a material that has undergone a process of partial solidification, followed by a subsequent partial recrystallization. This process leads to enhanced mechanical properties and ease of formability. This process also increases the material's resistance to deformation during processing. [Plonka 2016], [EN AW 1050A 2024], [Lipinska 2015]

Properties	Values
Thickness t[mm] from – to	0.5-1.5
Strength Rm [MPa] min – max	105 -145
Yield strength Rp 0.2 – min	75
HBS hardness	33

Table 1. Mechanical and physical properties of aluminium AW 1050 H24

2.2 *Experimental conditions*

2.2.1 *Sample preparation*

Prior to the application of the cataphoresis coating, it is imperative to meticulously prepare the material surface by ensuring its cleanliness and the absence of any impurities. The selection of aluminum type AW 1050A H24 was made on the basis of its favorable mechanical and chemical properties, as well as its composition, which contains up to 99.9% pure aluminum. Prior to the degreasing of the aluminum structural elements, the Wedolit CN 5370-22 type oil was applied to the surface of the material. The cutting oil in question is distinguished by its low viscosity, insolubility in water, and high thread-cutting performance. The technology is founded on the most recent advancements in base oil engineering [WEDOLIT 2024].

2.2.2 *Degreasing*

Two types of degreasing solutions were utilized to degrease the surface of the aluminum part, namely solution 1 and solution 2. The utilization of a range of solutions enabled a thorough evaluation of their efficacy in removing Wedolit CN 5370-22 oil from aluminum components. A multifaceted evaluation approach was employed, encompassing metrics such as cleaning efficiency, surface cleanliness, and the impact on subsequent manufacturing steps. This comprehensive evaluation process was undertaken to ascertain the most efficacious solution for achieving optimal degreasing and surface preparation prior to further treatments.

- *Degreasing Solution 1* is a strongly alkaline, slightly foaming and moderately emulsifying preparation designed especially for immersion and spray degreasing of steel and cast iron, which, due to the content of sodium carbonate (20-30 %), sodium metasilicate (20-30 %), sodium hydroxide (20-30 %) and fatty tallowamine (3-5 %), effectively removes stubborn preservative deposits and greasy impurities, but at higher concentrations of sodium hydroxide, a chemical reaction with aluminium occurs, leading to surface damage due to aluminate formation and hydrogen evolution.
- *Degreasing Solution 2* is an alkaline liquid cleaner containing silicates and borates, primarily designed for cleaning aluminium, but also suitable for steel and galvanised steel, and as a neutral cleaner for degreasing all metals using steam or high pressure cleaning, it is ideal for cleaning chassis, bodywork or engines, and its chemical composition consists of potassium hydroxide (3-5 %), disodium silicate (1-2 %), potassium-silica borate (7-10 %), silicic acid (5-7 %) and tri-potassium phosphate (10-12,5 %).

Controllable factors							
Factor Code	Factor	Unit	Factor level				
			-2	-1	0	+1	+2
x_1	k_{ODM}	%	0.782	1.5	4	6.5	7.218
x_2	t_{ODM}	min	1.138	2	5	8	8.861
x_3	T_{ODM}	°C	34.25	40	60	80	85.75

Table 2. Values of input variable factors

Subsequent to the degreasing process, a one-minute rinse was conducted in demineralized water to ensure the complete removal of residual detergents and any residual dirt.

2.2.3 *Cataphoretic coating*

For the cataphoretic coating, the parameters were set constant: a voltage of 270 volts, an application time of five minutes, and a current of 225 amperes (see Table 3). During the process, the temperature and solids concentration in the bath were meticulously monitored. Cataphoresis coating is an electrochemical process that facilitates the uniform application of protective coatings on complex surfaces, thereby enhancing their resistance to corrosion, chemical degradation, and mechanical wear. This method is intended to ensure a high-quality and durable protective surface.

Factor code	Factor	Unit	Value
x_4	U_{KTL}	V	270
x_5	I_{KTL}	A	225
x_6	T_{KTL}	°C	31.2
x_7	t_{KTL}	min	5

Table 3. Constant values of cataphoretic coating

Subsequent to the application of the cataphoretic coating, the hinge is rinsed with ultra-filtered water to eliminate any residual paint and chemical substances. This process has been demonstrated to enhance paint adhesion, augment corrosion resistance, and guarantee a satisfactory surface appearance.

2.2.4 *Polymerisation*

The process is finalized with a thorough rinsing with ultra-filtered water, which is then followed by the crucial stage of curing in an oven at approximately 200°C for 22 minutes. This process is intended to ensure maximum hardness and durability of the coating, thereby extending the life of the product by 10 to 15 years. Maintaining precise temperature and time parameters is paramount to prevent deformation. Polymerisation is a process that ensures the formation of a high-quality surface and the reliability of the material for industrial applications.

Factor code	Factor	Unit	Value
x_8	T_{polym}	°C	200
x_9	t_{polym}	Min	22

Table 4. Constant values of polymerisation

2.3 *Conical bend*

The bend test on a conical mandrel with a cylindrical frame is a common method for assessing the flexibility, adhesion, and resistance of surface coatings to cracking or peeling under deformation. The test is conducted in accordance with ISO 6860:2006, entitled "Coatings, flexural test (on conical mandrel)." The cut-out specimens exhibited a disruption in the surface layer, indicative of crack propagation. The testing was carried out using Gamin TQC SP 1831. The test method involves the application of force to a painted specimen by means of a conical mandrel of gradually varying diameter. The specimen is held in a cylindrical frame to ensure uniform loading. As the bending process is underway, an increase in stresses is observed within the coating. This rise in stress is attributed to the coating's adaptation to the shape of the mandrel. To ensure the reliability of the results, it is imperative to maintain a stable temperature of 23°C. The conical mandrel design enables the bending of the specimen over a diameter range of 3.1 to 38 mm, thereby facilitating the assessment of the coating's flexibility. The specimen is subjected to a 180° bend in a continuous manner for a duration of 2-3 seconds. Thereafter, an immediate inspection is conducted for any damage using a 10× magnifying glass and KEYENCE microscope. The dimensions of the damage, including its length and diameter, are meticulously measured using a digital instrument. The resulting data is systematically documented in a tabular report.

Figure 1. Bending test on conical mandrel TQC SP1831

3 RESULTS

Table 5 compares the ODM 1 and ODM 2 models according to the prediction quality indicators. The ODM 2 model shows higher values of both R^2 (0.98) and adjusted R^2 (0.92), implying a better explanation of the variability of the data compared to ODM 1 (R^2 0.81). The RMSE is significantly lower for ODM 2 (2.93), confirming a more accurate prediction. Although AICc is lower for ODM 1 (164.14), BIC favours ODM 2 (93.64), indicating a better balance between accuracy and model complexity. Thus, overall, ODM 2 performs better.

	ODM 1	ODM 2
RSquare	0.810084	0.979654
RSquare Adj	0.643907	0.923702
Root Mean Square Error	12.89776	2.927778
Mean of Response	33.5475	29.95625
Observations	16	16
AICc	164.1414	265.6011
BIC	141.0947	93.64477

Table 5. Summary of model fit

Table 6 provides the parameter estimates for the ODM 1 model and evaluates the significance of individual factors and their combinations on the crack length caused by the KTL process with degreasing solution 1, at a significance level of α = 0.05. The "Estimate" column shows the direction and magnitude of the effect – positive values increase the crack length, while negative values decrease it. "Std Error" represents the standard error, "t Ratio" is the ratio of the estimate to the error, and "Prob > |t|" indicates the probability of a Type I error, with values below 0.05 indicating statistical significance. The baseline value (Intercept) is 33.5475 mm, representing the crack length without the influence of any factors. The results show that the most significant factors affecting the crack length are temperature and its interactions with concentration and time, with some interactions having a significant negative effect.

Term	Estimates	Std Error	t Ratio	Prob>|t|
Intercept	33.5475	3.224441	10.4	<.0001*
x_3	16.32417	6.267187	2.6	0.0314*
$x_3 \cdot x_1$	12.00875	4.560048	2.63	0.0300*
$x_3 \cdot x_2$	-10.2088	4.560048	-2.24	0.0555
$x_1 \cdot x_2$	-11.8438	4.560048	-2.6	0.0318*
$x_3 \cdot x_3 \cdot x_3$	-4.33542	2.149627	-2.02	0.0784
$x_3 \cdot x_3 \cdot x_1$	9.97375	4.560048	2.19	0.0602
$x_3 \cdot x_1 \cdot x_2$	-8.75375	4.560048	-1.92	0.0912

Table 6. The table of parameter estimates for the ODM_01 model

Based on these estimates, a statistical predictive model can be constructed:

$$th_{ODM\_01} = 33.5475 + 16.32417 \cdot x_3 + 12.00875 \cdot x_3 \cdot x_1 - 10.2088 \cdot x_3 \cdot x_2$$
$$-11.8438 \cdot x_1 \cdot x_2 - 4.33542 \cdot x_3^3 + 9.97375 \cdot x_3 \cdot x_3 \cdot x_1 - 8.75375 \cdot x_3 \cdot x_1 \cdot x_2 \tag{1}$$

To construct the predictive relationship in its natural scale, it is important to note that during the analysis, the factors were used in the coded scale, with the DoE being normalized:

$$x_d(i) = \frac{x(i) - \frac{x_{max} + x_{min}}{2}}{\frac{x_{max} - x_{min}}{2}} \tag{2}$$

,where $x_d(i)$ - the DoE normalized variable , $x(i)$ - the original baseline variable , where i=1,2...n, n is the number of baseline factors, x_{max} - the maximum value of the original variable $x(i)$, x_{min} - the minimum value of the original variable $x(i)$. Considering the transfer relation (2) and the statistical equation (1), it is possible to write a prediction relation describing the investigated dependence for degreasing solution 1:

$$
\begin{aligned}
L_p = {} & 14.85420833 \cdot k_{ODM} + 0.5971666667 \cdot t_{ODM} - 0.8614585 \cdot tep + 2.402908333 \cdot k_{ODM} \cdot t_{ODM} \\
& - 0.8311041667 \cdot k_{ODM} \cdot tep + 0.121645 \cdot t_{ODM} \cdot tep \\
& + 0.0124671875 \cdot k_{ODM} \cdot tep^2 + 0.0476782 \cdot tep^2 \\
& - 0.0005419275 \cdot tep^3 - 0.07294791667 \cdot k_{ODM} \cdot t_{ODM} \cdot tep - 8.82950333
\end{aligned} \tag{3}
$$

Term	Estimates	Std Error	t Ratio	Prob>|t|
Intercept	27.57375	1.267765	21.75	<.0001*
x_3	-8.491667	1.422644	-5.97	0.0040*
x_1	-2.15125	0.731944	-2.94	0.0424*
x_2	5.4125	1.035126	5.23	0.0064*
$x_3 \cdot x_1$	3.9025	1.035126	3.77	0.0196*
$x_1 \cdot x_1$	3.030625	0.633882	4.78	0.0088*
$x_3 \cdot x_2$	2.255	1.035126	2.18	0.0949
$x_1 \cdot x_2$	6.49	1.035126	6.27	0.0033*
$x_2 \cdot x_2$	-0.648125	0.633882	-1.02	0.3644
$x_3 \cdot x_3 \cdot x_3$	2.4741667	0.487963	5.07	0.0071*
$x_3 \cdot x_3 \cdot x_2$	-10.4425	1.463889	-7.13	0.0020*
$x_3 \cdot x_1 \cdot x_2$	-3.025	1.035126	-2.92	0.0431*

Table 7. The table of parameter estimates for the ODM_03 model

The table 7 shows that the most significant influence on the output variable comes from temperature (negative effect), time (positive effect), and their mutual interactions. Combinations of concentration and time are also significant, as they increase the value of the variable. Several higher-order interactions and nonlinear effects (such as squared terms) also have a significant impact, indicating complex relationships between the factors. Overall, the model demonstrates that the outcome is affected not only by individual factors but especially by their combinations. Based on the table, it is therefore possible to construct a statistical model in the form of:

$$
\begin{aligned}
th_{ODM\_03} = {} & 27.57375 - 8.491667 \cdot x_3 - 2.15125 \cdot x_1 + 5.4125 \cdot x_2 \\
& + 3.9025 \cdot x_3 \cdot x_1 + 3.030625 \cdot x_1^2 + 2.255 \cdot x_3 \cdot x_2 + 6.49 \cdot x_1 \cdot x_2 \\
& - 0.648125 \cdot x_2^2 + 2.4741667 \cdot x_3^3 - 10.4425 \cdot x_3 \cdot x_3 \cdot x_2 - 3.025 \cdot x_3 \cdot x_1 \cdot x_2
\end{aligned} \tag{4}
$$

Considering the transfer relation (2) for the DoE normalization of the independent variables x1÷x3, the technological prediction model can be written in the form :

$$
\begin{aligned}
L_p = {} & 0.75765625 \cdot k_{ODM}{}^2 - 0.02520833333 \cdot k_{ODM} \cdot t_{ODM} \cdot tep + 2.59416667 \cdot k_{ODM} \cdot t_{ODM} \\
& + 0.2236041667 \cdot k_{ODM} \cdot tep - 25.96145833 \cdot k_{ODM} - 0.07201388889 \cdot t_{ODM}{}^2 \\
& - 0.008702083333 \cdot t_{ODM} \cdot tep^2 + 1.182666667 \cdot t_{ODM} \cdot tep - 41.43486111 \cdot t_{ODM} \\
& + 0.0003092708375 \cdot tep^3 - 0.01215833 \cdot tep^2 - 3.388041638 \cdot tep + 235.0609029
\end{aligned} \tag{5}
$$

With increasing concentration of the degreasing solution, a slight increase in the length of the cracks formed was observed at all application times evaluated, indicating a possible correlation between the degreasing efficiency and the adhesion of the cataphoretic coating. At short application times (1.138 min), the coating was applied in a thin, homogeneous layer with good flexibility and adhesion, resulting in the formation of short cracks in the range of 1-5 mm. Increasing the application time to 2 min caused the crack length to increase to 5-10 mm, reaching values of 15-22 mm at 5 min.

At the longest application time (8 minutes), the crack length increased significantly, to approximately 35 mm, which is related to the increased coating thickness. Thicker coatings are less flexible, more susceptible to internal stresses and thus to the formation of longer cracks under mechanical bending stresses.

Figure 2 shows the dependence of crack length (Lp) on the concentration of degreasing solution at different application times at a minimum temperature of 34.25 °C. The graph illustrates the relationship between the crack length and the concentration of the degreasing solution, as well as the application time. It demonstrates that the crack length is minimal at the shortest application time and increases with an extended application time.

The longest crack was identified at a deposition time of 8.861 minutes, with a maximum length of 42 millimeters. Prolonged deposition has been shown to result in the development of a porous and less homogeneous coating structure. Such a structure may contain microcracks and weak spots, which, under mechanical stress, may coalesce into longer cracks. The presence of residual substances on the surface, resulting from an inadequate degreasing process (specifically, degreasing solution 1), can compromise the integrity and quality of the applied coating. As the deposition time increases, these imperfections may become more pronounced, further diminishing the mechanical resistance of the coating. Consequently, it can be deduced that elevated degreasing concentrations and extended deposition times result in the formation of more substantial cracks, which may signify a diminished adhesion of the cataphoretic coating to the substrate.

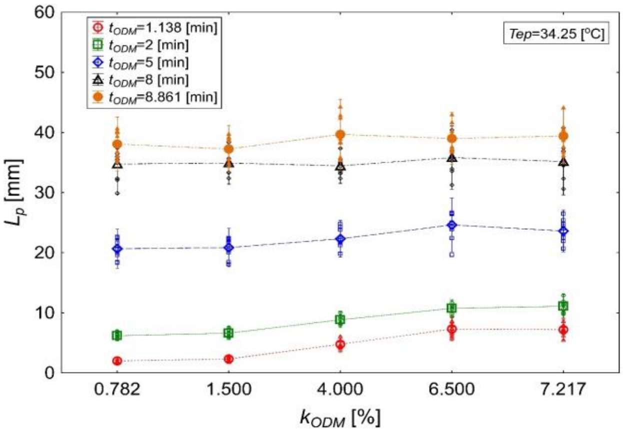

Figure 2. The dependence of crack length (*Lp*) on degreasing concentration at various deposition times at the minimum temperature of 34.25 °C

As illustrated in Figure 3, the crack length (Lp) exhibited a dependence on the concentration of the degreasing solution, with this dependence varying according to the application time. The analysis was conducted at an average temperature of 60°C. The graph illustrates the variation in crack length in response to alterations in solution concentration and application time, while concurrently monitoring the impact of degreasing on the quality of the surface treatment prior to the subsequent coating application. At a temperature of 60 °C, the crack length varies depending on the concentration of the degreasing solution and the deposition time. At the lowest concentration of 0.782 %, the cracks are the longest. At such a low concentration, grease and contaminants may not be completely removed, leading to weaker adhesion of the layer and reduced coating homogeneity. This results in a higher tendency for crack formation, especially at longer deposition times, where more pronounced internal stresses can develop within the coating. At the longest deposition time (tODM=8.861 min), defects can accumulate on the poorly degreased surface, causing an extreme increase in crack length up to 60 mm. Conversely, at the shortest time (tODM=1.138 min), the layer is thinner, and internal stresses are not as pronounced, which explains the shorter cracks of around 10 mm. In this case, structural defects caused by poor degreasing likely do not have enough time to fully develop. With increasing concentration (kODM=1.5 %), the crack length slightly increases at all deposition times but remains shorter at shorter deposition times. At a concentration of kODM=4 %, crack lengths become consistent across all deposition times at approximately 35 mm, indicating optimal coating cohesion without significant defects. As the concentration increases further to kODM=6.5 % and 7.217 %, an opposite trend occurs — crack lengths significantly decrease at longer deposition times, falling below 20 mm, while at shorter deposition times they increase up to 50 mm. This trend suggests that higher degreasing concentrations may lead to better coating quality at longer deposition times, whereas at shorter times they cause brittleness in the coating and longer cracks. Compared to the minimum temperature of 34.25 °C, we observe that at 60 °C, the extreme values are more balanced, with the influence of degreasing being more pronounced at higher concentrations, while at the lower temperature, the dominant effect was the deposition time.

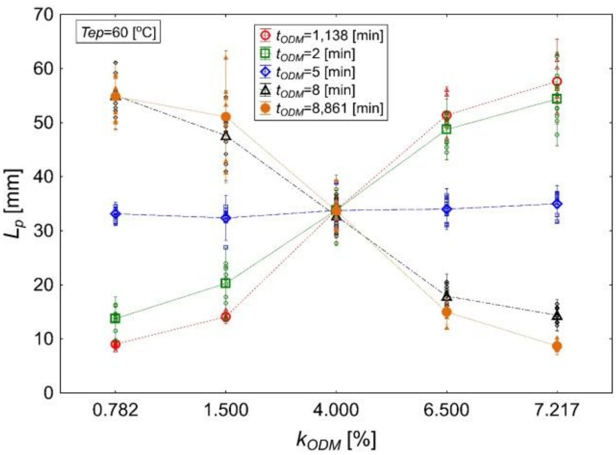

Figure 3. Dependence of crack length (*Lp*) on degreasing concentration at different deposition times at an intermediate temperature of 60 °C.

The figure 4 shows the microstructure of the defects formed after performing a flexural test, which investigates the effect of degreasing factors on the surface quality after a deformation adhesion test of the coating. In figure (4a), the surface is visible with fine cracks and local coating deviations, indicating the average quality of the pre-degreasing. The defects appear as fine lines in the bending area, with no massive flaking present. At kODM = 6.5 %, tODM = 8 min, TODM = 80 °C (Fig. 4b), the surface is significantly damaged by peeling off a large part of the coating at the bending point, indicating that the coating has lost cohesion and separated from the substrate. This phenomenon may be the result of too high a concentration of degreasing solution, which may have disturbed the substrate surface or caused excessive activation, impairing the adhesion of the cataphoresis varnish. Figure (4c) shows uneven flaking of the coating and significant destruction at the bending point, with residual contaminants visible on the surface. Interpretation: Inadequate degreasing caused residual dirt and grease on the surface, resulting in poor adhesion of the coating to the substrate.

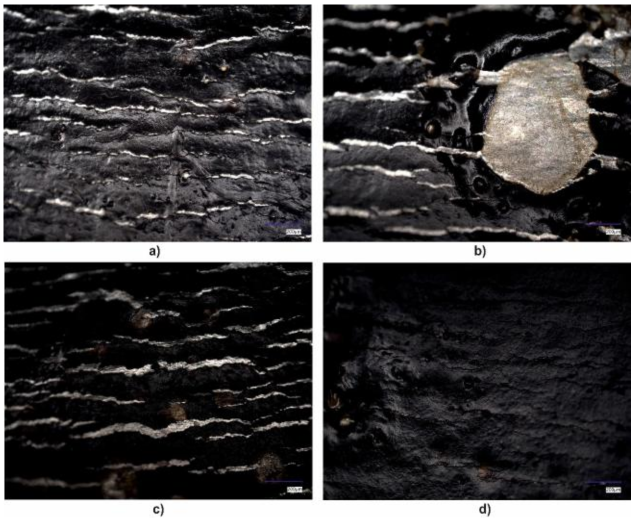

Figure 4. The nature of the surface of the cataphoretic layer and the basic errors when using degreasing solution 1: [a) k_{ODM}=1.5 %, t_{ODM}=8 min, T_{ODM}=80 °C]; [b) k_{ODM}=6.5 %, t_{ODM}=8 min, T_{ODM}= 80 °C]; [c) k_{ODM}=0.782 %, t_{ODM}=5 min, T_{ODM}=60 °C]; [d) k_{ODM}=7.217 %, t_{ODM}=5 min, T_{ODM}=60 °C];

After mechanical stress, the coating separated easily. At k_{ODM} = 7.217 %, t_{ODM} = 5 min, T_{ODM} = 60 °C (figure 4d), the surface appears smooth, but small cracks and micro flaking are present at the bending point. Interpretation: High concentration of degreasing solution at low temperature and short time may cause uneven degreasing and stresses in the coating, which were released in the form of microcracks and partial flaking during the bending test. Insufficient or excessive degreasing significantly affects the results of the bending test. Optimum conditions should ensure a clean surface without damage to the substrate so that the cataphoretic coating can form a strong and flexible bond. The greatest problems in bending occur at the extremes (4b and 4c).

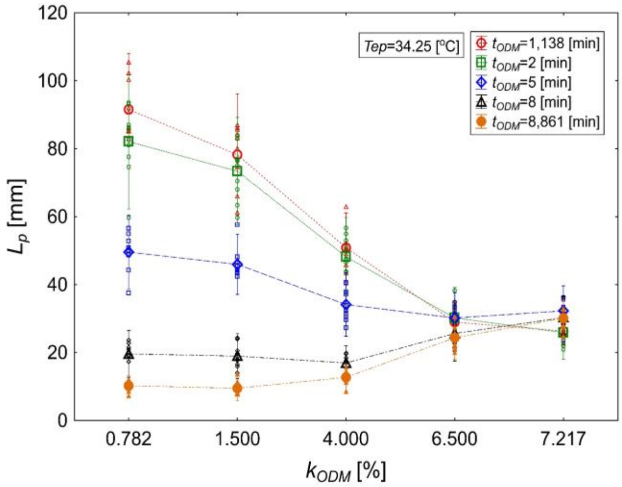

Figure 5. The dependence of crack length (*Lp*) on degreasing concentration at various deposition times at the minimum temperature of 34.25 °C

The graph (Figure 5) illustrates the relationship between crack length (*Lp*) and degreasing solution concentration (k_{ODM}) at varying application times (t_{ODM}) for degreasing solution no. 2 at a minimum degreasing temperature of 34.25 °C. At low concentrations ranging from 0.782 % to 1.5 %, substantial crack expansion was observed at brief application times. For instance, at t_{ODM}=1.138 min, the crack length can extend up to 100 mm, while at t_{ODM}=2 min it reaches approximately 80 mm. This phenomenon suggests that at low concentrations and low temperatures, the degreasing process is not sufficiently effective, resulting in structural defects and compromised coating adhesion. The underlying cause is attributed to the inadequate removal of grease and organic contaminants from the material surface at such low concentrations. Insufficient surface treatment can result in two main issues: first, uneven substrate coverage, and second, uneven coating structure. Additionally, the low temperature of 34.25 °C slows down the chemical reactions in the solution, reducing its effectiveness and the readiness of the surface for subsequent coating application. A substantial decrease in crack length was observed at intermediate concentrations ranging from 4 % to 6.5 %. While the curves at t_{ODM}=1.138 min and t_{ODM}=2 min continue to exhibit relatively elevated values within the range of 50 to 70 mm, a substantial decline is observed in comparison to lower concentrations. This observation indicates that at these higher concentrations, surface degreasing is more effective, thereby improving the surface quality prior to the coating application process. This phenomenon can be attributed to the enhanced efficiency of the solution in removing organic contaminants and grease, thereby eliminating numerous structural defects that could impede coating adhesion. Concurrently, intermediate concentrations guarantee superior surface tension homogeneity, thereby diminishing the probability of microcracks and internal stresses within the coating. The enhanced degreasing efficiency also fosters more uniform coating distribution and superior adhesion of the coating to the substrate, thereby curtailing the formation and propagation of cracks. This phenomenon elucidates the observed stabilization and reduction in crack length at medium concentrations compared to low concentrations. At a degreasing concentration of 7.217 %, the crack length stabilizes, reaching its lowest values, particularly at t_{ODM}=8 min and t_{ODM}=8.861 min, with cracks under 20 mm. This indicates optimal contaminant removal and surface preparation, ensuring strong coating adhesion and minimizing defects. The effectiveness is likely enhanced by the chemical composition of the Chemetall degreasing agent, which at higher concentrations ensures uniform distribution and better surface reaction. Proper degreasing minimizes uneven stress on the coating, reducing crack formation and propagation.

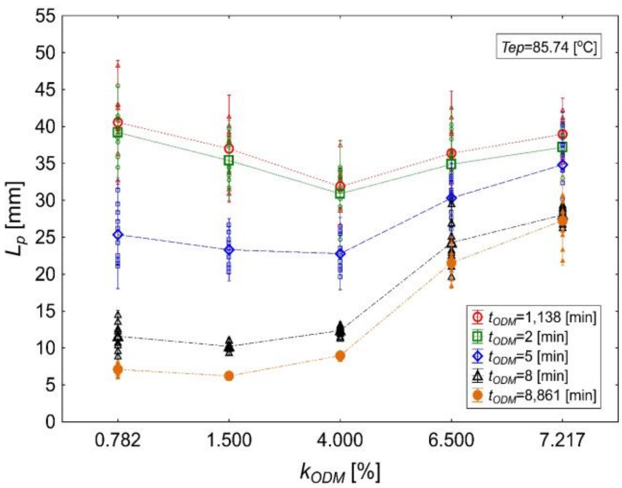

Figure 6. The dependence of crack length (*Lp*) on degreasing concentration at various deposition times at the maximum temperature of 85.74 °C

The graph (Figure 6) illustrates the relationship between the crack length (*Lp*) and the concentration of the degreasing solution (k_{ODM}) at varying application times (t_{ODM}) for solution No. 3, under maximum solution temperature conditions of 85.74 °C. At low degreaser concentrations (0.782 % to 1.5 %), significant crack enlargement occurs at short application times, with crack lengths of up to 100 millimeters at t_{ODM}=1.138 minutes and approximately 80 millimeters at t_{ODM}=2 minutes. A low concentration signifies that there is a limited quantity of active ingredients (i.e., degreasing agents) in the solution, which are responsible for the chemical breakdown and removal of grease and dirt. Consequently, a residue of dirt is left on the surface, impeding the subsequent preparation of the surface for the next coating process. As the concentration increases, the crack length decreases or stabilizes; however, at higher concentrations above approximately 6.5 %, the crack length increases again. The smallest observable crack length typically manifests at medium degreaser concentrations of approximately 4 %, suggesting that these conditions are optimal for minimizing crack growth. Shorter application times (1.138 minutes) result in larger cracks, while longer times (8.861 minutes) contribute to their reduction, indicating a beneficial effect of extended application time on the quality of the coating.

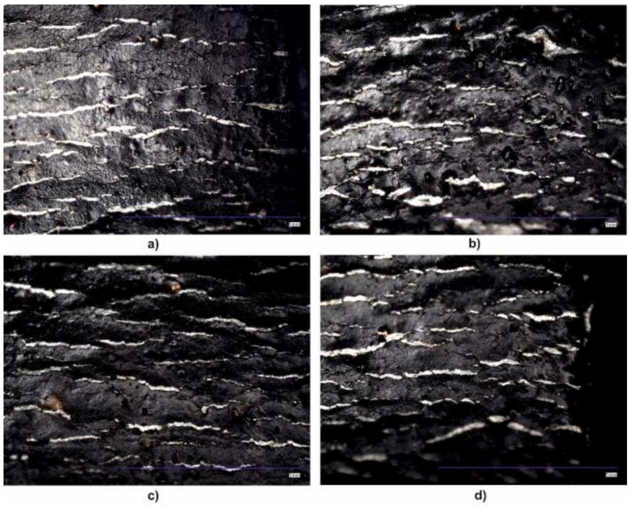

Figure 7. The nature of the surface of the cataphoretic layer and the basic errors when using degreasing solution 1: [a) k_{ODM}=1.5 %, t_{ODM}=8 min, T_{ODM}=80 °C]; [b) k_{ODM}=6.5 %, t_{ODM}=8 min, T_{ODM}= 80 °C]; [c) k_{ODM}=0.782 %, t_{ODM}=5 min, T_{ODM}=60 °C]; [d) k_{ODM}=7.217 %, t_{ODM}=5 min, T_{ODM}=60 °C];

When k_{ODM} is set to 1.5 %, t_{ODM} is set to 8 minutes, and T_{ODM} is set to 80 °C (Fig. 8a), the surface is relatively clean, with visible grooves, but small residues of dirt are still present. The low concentration leads to a partial removal of impurities, resulting in a surface that is not completely homogeneous. Conversely, when the concentration is augmented to 6.5 %, maintaining a constant deposition time and an elevated temperature of 80 °C (refer to Figure 8b), the surface attains substantial uniformity, exhibiting negligible residual impurities. It is evident that an elevated concentration, elevated temperature, and adequate exposure time collectively ensure effective degreasing and facilitate more optimal preparation for subsequent surface treatment. Conversely, an elevated degreasing concentration (0.782 %) necessitates an augmented deposition time (5 minutes) and an elevated temperature (60 °C). This results in a distinctly inhomogeneous surface, characterized by evident dirt residues and surface defects. The combination of low concentration, reduced temperature, and abbreviated exposure duration leads to inadequate impurity removal, consequently compromising surface preparation for cataphoresis. Conversely, at k_{ODM}=7.217 %, t_{ODM}=5 min, and T_{ODM}=60 °C (Figure 8d), the surface is visibly uneven, exhibiting substantial damage to the surface layer. The elevated concentration of the solution, in conjunction with the reduced temperature, precipitates a vigorous reaction of the solution with the material, culminating in surface degradation. It can be inferred that the optimal configuration of degreasing parameters is instrumental in ensuring surface quality prior to cataphoresis coating. Insufficient cleaning is a consequence of employing low concentrations and temperatures; conversely, elevated concentrations have the potential to compromise the surface integrity. The most suitable combination in this case appears to be a setting of k_{ODM}=6.5 %, t_{ODM}=8 min, and T_{ODM}= 80°C, which provides a quality degreasing without compromising the surface integrity.

4 DISCUSSION

The results of my research have also been analysed using a decision tree, which provides a clear view of how the various factors of the manufacturing process affect the length of the crack after the bend test in cataphoretic painting. This visual and analytical tool helps to identify the key variables that have the most significant impact on the final coating condition.

The decision tree illustrates (Figure 8) the influence of various factors of the manufacturing process on the crack length after a bend test in cataphoretic painting. The main factors considered in this tree include the concentration of the solution in the process, the deposition time, the temperature and the method of degreasing the surface before coating. At the very beginning of the tree, the concentration of the solution plays a critical role, with the process proceeding through the left branch of the tree if it is less than or equal to 5.25 % but moving to the right branch if it is greater than 5.25 %.

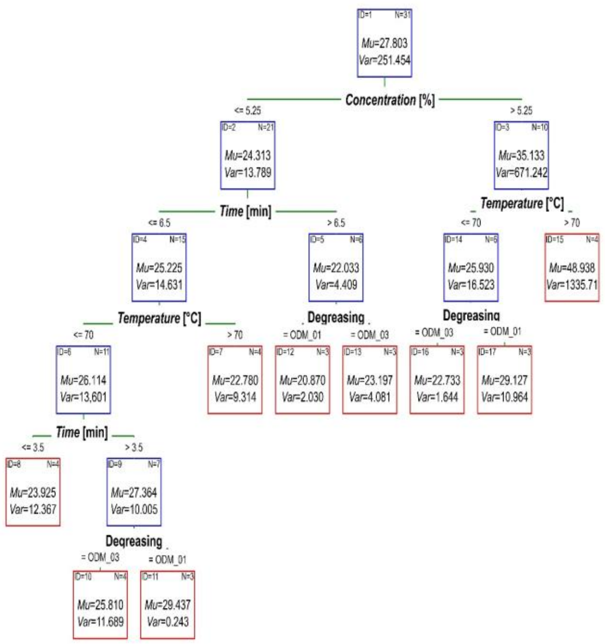

Figure 8. This study explores the impact of various input variables on changes in the quality of the surface of the cataphoresis layer when employing degreasing solutions 1 and 3.

At lower solution concentrations, deposition time impacts the result, with temperature becoming crucial when the time is ≤ 6.5 minutes. Temperatures above 70 °C with short deposition times lead to cracks (avg. 22.780 mm) due to accelerated curing, uneven layer distribution, and reduced coating elasticity. High temperatures also cause volatile component evaporation and internal stresses, weakening adhesion and increasing brittleness.

At temperatures up to 70 °C and deposition times up to 3.5 minutes, the average crack length is 23.925 mm. With extended deposition times, the type of degreaser affects the outcome. ODM 2 results in a crack length of 25.810 mm, while the more aggressive ODM 1 leads to 29.437 mm due to its higher sodium hydroxide content, which erodes the aluminum surface and increases internal stress. For longer deposition times (>6.5 minutes), ODM 1 produces better results with an average crack length of 20.870 mm, while ODM_02 causes uneven etching, increasing crack length to 23.197 mm.

At higher concentrations above 5.25 %, the process temperature plays a role, where at temperatures up to 70 °C, the decision is again based on the degreasing method. If ODM 2 is used, the average crack length is 22.733 mm with a variance of 1.644, which is a very stable and desirable result, while when ODM 1 degreasing is used, the value rises to 29.127 mm with a higher variance of 10.964, which already indicates a less favourable condition. Thus, overall, at higher solution concentration, ODM 2 is more gentle to the aluminum surface and prevents excessive chemical attack, while ODM 1 with sodium hydroxide is too chemically reactive and causes more damage. At temperatures above 70°C, there is an enhancement in chemical reactivity, an increase in internal stresses within the material, and a destabilization of the painting process. This results in the manifestation of prolonged cracks and a considerable increase in the variability of the results. Consequently, it can be concluded that optimal results are achieved with lower concentrations up to 5.25%, extended process times above 6.5 minutes, and the utilization of degreasing type ODM 1, where the crack length values are minimal and the dispersion is negligible. Alternatively, higher concentrations can be employed, provided that the temperature is maintained at up to 70°C and degreasing type ODM 2 is used. Conversely, the most unfavorable outcomes are attained through the convergence of elevated concentration and elevated temperature, where the crack length undergoes a substantial augmentation and the variability of the outcomes attains an extreme magnitude, signifying elevated instability and the potential for substandard coating quality. Consequently, this decision tree serves as a valuable instrument for the optimization of the coating process, as it facilitates the identification of conditions conducive to optimal coating quality and the minimization of defects, such as cracks. It is evident that the process demonstrates a high degree of sensitivity to the simultaneous presence of elevated temperature and concentration levels. To ensure the optimal performance of the coating, it is imperative to meticulously monitor and adjust these parameters, thereby maximizing durability and minimizing defects.

5 CONCLUSIONS

A comparative analysis was conducted of the impact of degreasing solutions 1 and 2 on the quality of cataphoretic coatings. The findings revealed that these solutions exhibited divergent effects on the formation of cracks in coatings, contingent on factors such as concentration, deposition time, and temperature. Solution 1 demonstrates a propensity to augment the crack length at elevated concentrations, exhibiting an optimal concentration of approximately 4%, at which point a stabilization of the crack length at approximately 35 mm is attained. Conversely, Solution 2 demonstrates superior performance at intermediate concentrations (4% to 6.5%) and temperatures around 80°C. At these conditions, the crack length is reduced, and optimal coating quality is attained without incurring surface damage. Degradation of the coating quality has been observed to occur at concentrations that are either too low or too high. This phenomenon is more pronounced for solution 1 at concentrations below 1.5% and for solution 2 at concentrations above 6.5%. The duration of the deposition process is also a critical factor. For deposition times of 1-2 minutes, both cases resulted in thin and homogeneous coatings. However, for longer deposition times, the layers became thicker and less flexible, accompanied by the formation of larger cracks. Solution 2 demonstrates enhanced stability and quality at extended deposition times (8 minutes). Conversely, solution 1 exhibits a more substantial increase in cracking at prolonged times, suggesting a decline in coating flexibility. Basic results:

- Solution 1 demonstrates enhancement at moderate concentrations (4 %) and brief application periods. However, at elevated concentrations or protracted application times, a decline in coating quality is observed.
- Solution 2 demonstrates optimal efficacy at concentrations of 6.5 % and a temperature of 80 °C, while preserving its optimal properties at extended application times.

ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-21-0228, and by the projects VEGA 1/0371/23 granted by the Ministry of Education, Research, Development and Youth of the Slovak Republic. This publication is the result of the Project implementation: Development of excellent research capacities in the field of additive technologies for the Industry of the 21st century, ITMS: 313011BWN5, supported by the Operational Program Integrated Infrastructure funded by the ERDF.

REFERENCES

[Brown 2016] Brown, N., et al. Environmentally Assisted Cracking Measurements in Structural Aluminum Alloys Under Accelerated Test Conditions. Corrosion, November 2016, Vol.72, No.11, pp 1351-1362. https://doi.org/10.5006/2085

[Dobránsky 2023] Dobránsky, J., et al. A Determination of the Influence of Technological Parameters on the Quality of the Created Layer in the Process of Cataphoretic Coating. Metals, June 2023, Vol.13, No.6, 1080. https://doi.org/10.3390/met13061080

[EN AW 1050A 2024] Materials Processing Europe GmbH. (2024). EN AW 1050A | Al 99.5. Thyssenkrupp Materials Processing Europe. Available online: https://www.thyssenkrupp-materials-processing-europe.com/en/aluminum/alloy-group-1000-or-en-aw-1050-a-or-en-aw-1200a/en-aw-1050a

[Fejko 2024] Fejko, P., et al. Analysis of the effect of pretreatment on the overall damage of the coating created by the cataphoretic coating. MM Science Journal, October 2024, Vol.4, pp 7576. https://doi.org/10.17973/MMSJ.2024_10_2024081

[Fejko 2024] Fejko, P., et al. Monitoring of Technological Factors to Change the Length of the Crack Created by Cataphoretic Coating. Innovations in Mechanical Engineering III, July 2024, pp 287-295. https://doi.org/10.1007/978-3-031-62684-5_26

[Flores 2011] Flores, J.F., et al. Assessing the resistance of metal matrix composites and their microstructural integrity under erosion–corrosion. Wear, July 2011, Vol.271, No.9–10., pp 1331–1340. https://doi.org/10.1016/j.wear.2010.12.027

[Kirchgeorg 2018] Kirchgeorg, T., et al. Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment. Marine Pollution Bulletin, November 2018, Vol.136., pp 257-268. https://doi.org/10.1016/j.marpolbul.2018.08.058

[Lipinska 2015] Lipinska, M., et al. Microstructure and mechanical properties of friction stir welded joints made from ultrafine grained aluminium 1050. Materials & Design, 2015, Vol.88, pp 22-31. https://doi.org/10.1016/j.matdes.2015.08.129

[Mason 2003] Mason, R.L., et al. Statistical design and analysis of experiments: with applications to engineering and science. New York: Wiley-Interscience, 2003. ISBN 0-471-37216-1.

[Oberreiter 2021] Oberreiter, M., et al. Impact of microstructural properties on the crack threshold of aluminium castings. Engineering Fracture Mechanics, January 2021, Vol.241, pp 107431. https://doi.org/10.1016/j.engfracmech.2020.107431

[Peti 2024] Peti, D., et al. The effect of degreasing temperature on the thickness of the formed layer created by cataphoretic painting. MM Science Journal, October 2024, ISSN 1805-0476. https://doi.org/10.17973/MMSJ.2024_11_2024085

[Plonka 2016] Plonka, B., et al. Studies of the AA2519 Alloy Hot Rolling Process and Cladding with EN AW-1050A Alloy. Arch. Metall. Mater, 2016, Vol.61, No.1, pp 381–388. https://doi.org/10.1515/amm-2016-0070

[WEDOLIT CN 5370-22 2024] WEDOLIT CN 5370 – 22, Master Fluid Solutions, 2016 – 2024, Europe, [online]. [10.06.2024]. Available from https://www.masterfluids.com/eu/en/products/show-product-description.php?pid=CN-5370-22

CONTACTS:

Patrik Fejko, MSc.
Technical University of Kosice, Faculty of Manufacturing Technology with seat in Presov
Bayerova 1, Presov, 08001, Slovakia
Institution/University, Department
+421948341916, patrik.fejko@tuke.sk, fvt.tuke.sk