

THE EFFECT OF COOLING AFTER GALVANIZING ON COATING COHESION DURING SWEEPING

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The paper focuses on analysing the effect of cooling immediately after the hot-dip galvanizing process on the cohesion of the zinc coating after subsequent sweeping. Various cooling methods were experimentally evaluated in terms of their impact on internal stress and coating adhesion. Particular attention was paid to the formation of defects such as delamination or cracks, which negatively affect the quality of the coating during mechanical cleaning. The results show that an inappropriate cooling method can lead to a disruption in the integrity of the protective layer and thus to a reduction in its corrosion resistance. The adhesion and cohesion of the zinc coating was experimentally verified using a pull-off test, while the behaviour of the coating under mechanical stress was analysed using a bending test. Additional metallographic analysis made it possible to identify any defects and faults in the microstructure of the coating. Based on the tests performed, no significant negative effect of the cooling regime after galvanizing on the cohesion of the coating during the sweeping process was demonstrated.

KEYWORDS

Sweeping, surface treatment, bending test, tear test, adhesion

1 INTRODUCTION

Zinc coatings are among the most widely used methods of corrosion protection for metallic materials, especially steel. Their effectiveness lies in the combination of barrier protection and cathodic action, where zinc acts as a sacrificial anode in relation to the ferrous substrate [ISO 9223, Zhang 1996].

Hot-dip galvanizing (HDG) is one of the most commonly used coating methods in the construction, energy, transport infrastructure, and engineering industries. The process involves immersing a steel semi-finished product in molten zinc, which causes a diffusion reaction between the iron and zinc and the formation of intermetallic phases that ensure high mechanical resistance and long service life of the coating [Cook 2015, Kuklik 2016].

In addition to standalone use, hot-dip galvanized surfaces are often used as part of so-called duplex systems, where they are subsequently coated with organic paints to increase their aesthetic value and further extend their corrosion protection [Sternadelova 2024]. However, before applying the coating, the zinc surface must be mechanically treated, most commonly using a sweeping method, which involves gentle blasting with a low-abrasive material. This process aims to create a suitable adhesive surface for the coating, but under certain conditions it can lead to disruption of the cohesion of the zinc coating, especially in the case of internal stress or the initiation

of microcracks during cooling after galvanizing [Goodwin 2018, Gnot 1999].

One of the potential risk factors that can affect the cohesion of the zinc coating during sweeping is the cooling method immediately after the galvanizing process [Stahl 2015]. In industrial practice, rapid water cooling is commonly used to increase productivity and reduce processing time. Although this stabilizes the temperature profile of the product, it can cause internal stresses, affect the growth of intermetallic phases, and lead to microcracks in the coating [Marder 2000].

The transition from extremely high to low temperatures within a few seconds can negatively affect the microstructure of the coating, and the influence of this process on its mechanical behaviour has not yet been sufficiently described.

The aim of this study is to experimentally assess the effect of modifying the cooling regime, specifically omitting water cooling after galvanizing, on the cohesion and mechanical integrity of the zinc coating during the sweeping process. As part of the experimental part, samples with different cooling regimes will be prepared and subsequently subjected to pull-off and bending tests to evaluate the adhesion and plasticity of the coating. Additional metallographic analysis will enable the identification of microstructural changes and the presence of any defects in the zinc layer. The results may contribute to the optimization of the hot-dip galvanizing process and increase the reliability of coating systems in demanding operating conditions.

2 RESEARCH MATERIALS AND RESEARCH METHODOLOGY

2.1 Materials

For the purposes of the experimental investigation, eight types of samples made of S235 structural steel were selected. These samples were subjected to hot-dip galvanizing in accordance with the ČSN EN ISO 1461 standard. Subsequently, the zinc coating was tested to evaluate the effect of subsequent cooling on its cohesion under mechanical stress using the sweeping method. The samples were in the form of flat bodies and tubes, which made it possible to compare the response of different shape configurations under identical conditions.

Prior to galvanizing, standard surface pretreatment was performed, including degreasing, pickling, fluxing, and drying. The hot-dip galvanizing process was carried out at a temperature of 444 °C with a dip time not exceeding five minutes. Chemical composition of molten zinc bath is shown in Table 1.

el.	Zn	Pb	Fe	Bi	Sn
wt. %	99,7090	0,1959	0,0258	0,0172	0,0151
el.	Cu	Sb	In	Ag	Ti
wt. %	0,0105	<0,0100	<0,0050	<0,0020	<0,0020
el.	Mn	Ni	Al	Cd	Mg
wt. %	<0,0020	<0,0020	<0,0020	<0,0006	<0,0005

Table 1. Chemical composition of molten zinc bath

After galvanizing, the samples were divided into two main groups – cooled and uncooled – and further into subgroups according to the sweeping application. The samples were cooled in clean water without additives; the uncooled samples cooled naturally in the air. An overview of the sample distribution is shown in Table 2 and Figure 1.

Flat samples 100x100x5 mm	Pipes Ø 80 mm
1 uncooled, unswept	1 uncooled, unswept

2 cooled, unswept	2 cooled, unswept
3 uncooled, swept	3 uncooled, swept
4 cooled, swept	4 cooled, swept

Table 2. Sample classification

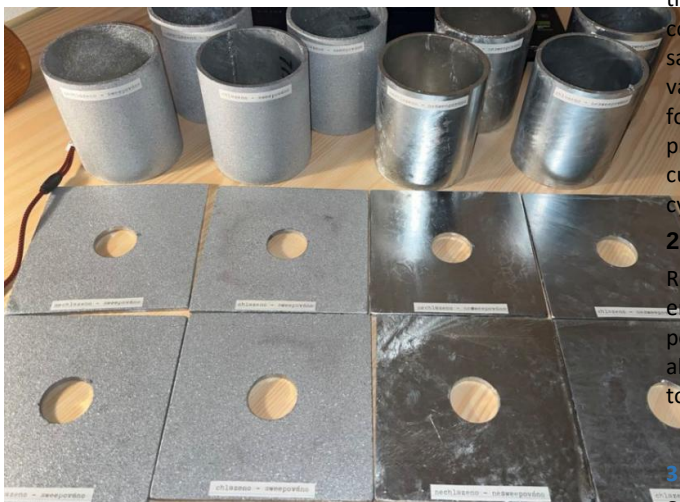


Figure 1. Testing samples

The chemical composition of the S235 structural steel used is specified in Table 3.

C	P	S	N
wt. %			
max. 0,170	max. 0,045	max. 0,045	max. 0,009

Table 3. Chemical composition steel S235

2.2 Sweeping

After the coating had cured, all samples were subjected to sweeping in accordance with the recommendations of standards ČSN EN ISO 12944-5 and ČSN EN ISO 1461 – Annex C, using low-abrasive corundum material (F120) at a pressure of 0.4 MPa and a nozzle distance of 200 mm. Sweeping was applied evenly from one side for 10 seconds.

2.3 Mechanical testing

Pull-off Test

To evaluate the adhesion of the coating, a standardized pull-off test was performed in accordance with ČSN EN ISO 4624, using cyanoacrylate adhesive to bond peel test specimens. The measurement was performed using an Elcometer 506 peel tester.

Bend Test

The behaviour of the coating under mechanical stress was evaluated using a bending test on a DP 2000 hydraulic press. The increase in force was recorded as a function of deformation for all types of samples, and defects caused by plastic deformation were then evaluated. The aim of the test was to observe the occurrence of any macroscopic defects, such as flaking or cracking of the zinc coating, and thus to compare the cohesion and adhesion to the substrate between cooled and uncooled samples. The bending test was performed in accordance with the recommendations set out in the ČSN EN ISO 7438 standard. A constant mandrel speed of 10 mm.min⁻¹ was used for the test.

Flattening Test

The tube samples were tested using a basic mechanical test, i.e., a crush test. The test was performed on a DP 2000 hydraulic press using a constant pressure plate feed rate of

10 mm/min, i.e., in accordance with the recommendations of the ČSN EN ISO 8492 standard.

The bending test and compression test were performed at an ambient temperature of 24 °C. In order to expand the possibilities for a detailed analysis of the effect of cooling conditions after galvanizing on the cohesion of the coated samples, the force curves were measured. The individual force values were measured using a strain gauge sensor calibrated for the maximum rated pressing force of the DP 2000 hydraulic press, i.e. 2 MN. The path was measured according to the current position of the working plate installed on the hydraulic cylinder of the press.

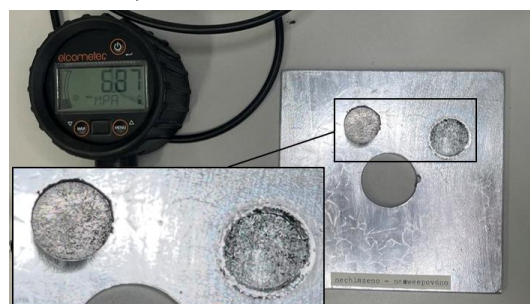
2.4 Metallographic analysis

Representative cross sections were taken from all groups, embedded in epoxy resin, and then prepared by grinding and polishing. The resulting section not only provided information about the quality of the coating but also made it possible to measure the thickness of the zinc coating

3 RESULTS AND DISCUSSION

3.1 Pull-off Test

Figure 2 shows the fracture surfaces and maximum stress values at cohesion failure. In all cases, cohesion failure occurred in the adhesive layer.



Sample 1: uncooled; unswept



Sample 2: cooled, unswept



Sample 3: uncooled, swept



Sample 4: cooled, swept

Figure 2. Fracture surfaces and maximum stress values cohesion failure

In all four tested sample variants, the adhesive layer was clearly identified as the weakest link in the connection system (substrate – zinc coating – adhesive – test specimen) by means of a pull-off test. No failure occurred either within the zinc coating itself or at its interface with the steel substrate, which indicates a high level of adhesion to the substrate and internal cohesion of the zinc layer applied by hot-dip galvanizing.

The measured values of maximum stress at the moment of failure showed some variation, which can most likely be attributed to minor deviations in the surface pretreatment prior to adhesive application or slight differences in the thickness of the adhesive layer itself.

In all tested cases, the zinc coating remained visually intact, with no signs of mechanical damage or delamination. Based on these findings, it can be concluded that the pull-off test did not show any negative effect of additional cooling after the galvanizing process on the adhesion or cohesion of the resulting coating.

3.2 Bending and Flattenig Tests

A bending test was performed to verify the plasticity and cohesion of the coating under mechanical deformation. As part of the test, flat samples were bent to an angle of 180°, causing significant stretching of the zinc coating on the outside of the bend and compression on the inside at ambient temperature. This severe deformation significantly exceeds the normal operating loads to which structural elements are typically subjected and represents a scenario for verifying the coating's resistance under extreme conditions.

The bending process of the flat samples is shown in Figure 3.

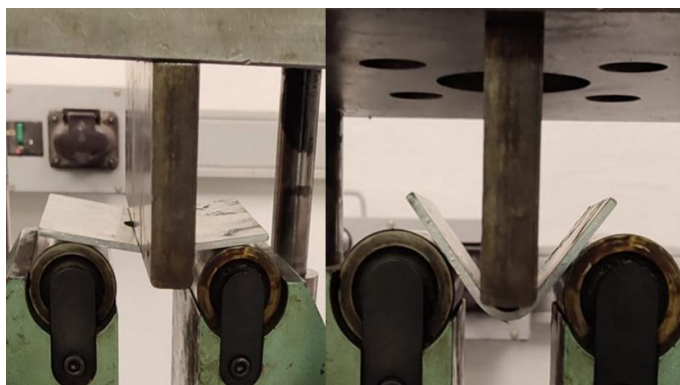


Figure 3. Bending test procedure for flat samples

In Figure 4, the measured force–displacement curves (bending force as a function of punch displacement) are presented. The curves clearly show the effect of swept on the resulting maximum values of the measured bending forces. The combination of a zinc coating with prior swept represents a mechanism that primarily affects the friction conditions

during subsequent bending. Considering the higher adhesion of the coating system when swept is applied, a longer coating life can be expected (i.e., a greater bending depth without the initiation of macroscopic failure). At the same time, the roughness of the resulting specimen surface has a significant influence on the friction conditions during bending, particularly at the contact points under the punch and at the supports. Swept samples exhibit higher surface roughness; therefore, higher maximum bending force values can be observed for these samples. For swept samples, the maximum bending force was found to be 13.8 kN (uncooled) and 12.7 kN (cooled). For non-swept samples, the maximum measured bending force values were 11.3 kN (uncooled) and 8.9 kN (cooled).

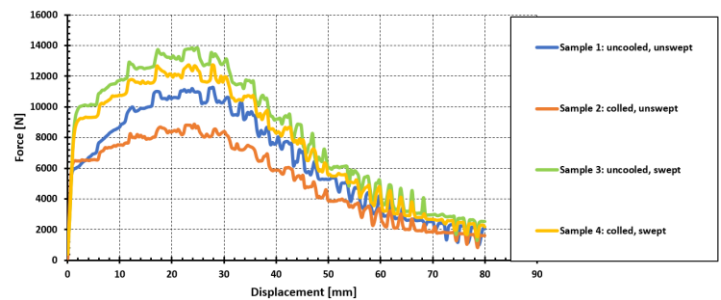
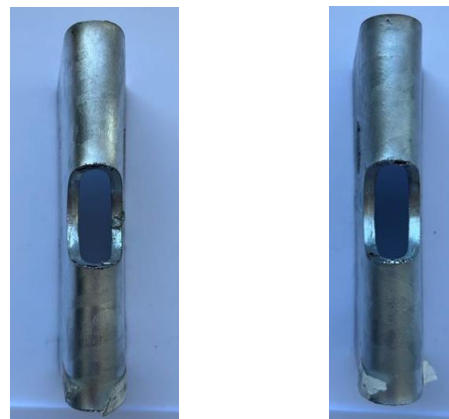


Figure 4. Diagram showing the force curve as a function of deformation

Figure 5 shows a visual comparison of flat samples after the bending test.



Sample 1: uncooled, unswept

Sample 2: cooled, unswept



Sample 3: uncooled, swept



Sample 4: cooled, swept

Figure 5. Flat samples after bending test

Swept samples immediately after the bending test showed similar behaviour to non-swept samples. Both types of samples had slightly reduced cohesion of cooled samples compared to uncooled samples.

The tubes were crushed on the same DP 2000 hydraulic press and under the same conditions as the flat samples. The crushing process of the tubes and a graphical representation of the increase in force depending on the deformation process are shown in Figures 6 and 7 below.

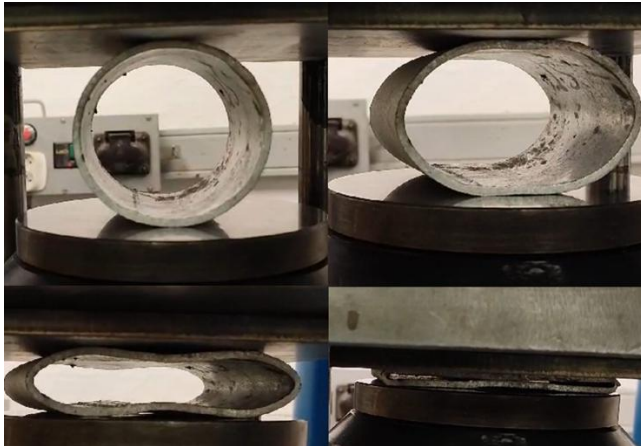


Figure 6. Pipe flattening test procedure

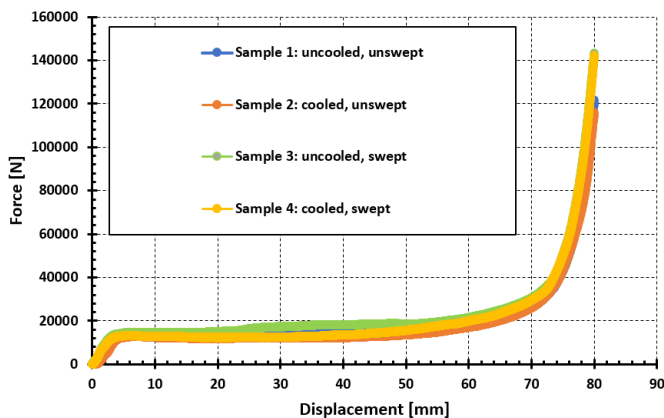


Figure 7. Graphical representation of force versus deformation

The pressing force curve shows a similar pattern for all tested samples. However, in the initial deformation phase, there is a slight increase in the required pressing force for uncooled samples compared to those that were cooled after galvanizing. In the final phase of the pressing process, on the other hand, a slightly increased pressing force is observed in samples with a swept surface compared to samples without sweeping.

Figure 8 shows a visual comparison of the tubes immediately after the crush test



Sample 1: uncooled, unswept



Sample 2: cooled, unswept



Sample 3: uncooled, swept



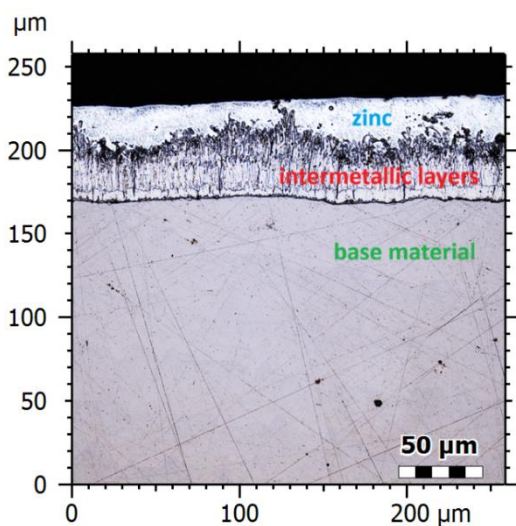
Sample 4: cooled, swept

Figure 8. Samples immediately after flattening testing

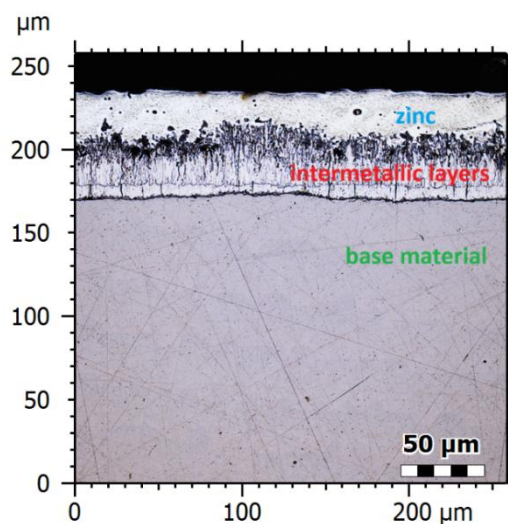
In unswept samples, we can observe minor local damage to the coating's integrity, especially near sharp edges, and to a greater extent in uncooled samples. In cooled samples, this phenomenon occurs minimally. In swept uncooled samples, we can again observe local damage to the coating's cohesion, especially near sharp edges (see Fig. 8). In swept cooled samples, this phenomenon also occurs to a minimal extent.

3.3 Metallographic analysis

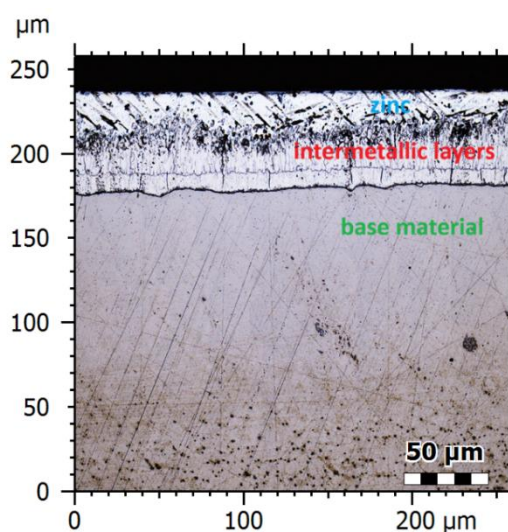
Metallographic analysis was used to compare zinc layers and perform destructive measurements of zinc layer thickness. Figure 9 below shows individual cross-sections of flat samples. The figures show the distribution of zinc and intermetallic layers. Samples 1 and 2, which were not swept, show a uniform zinc layer. In contrast, samples 3 and 4 have an uneven zinc layer after sweeping.



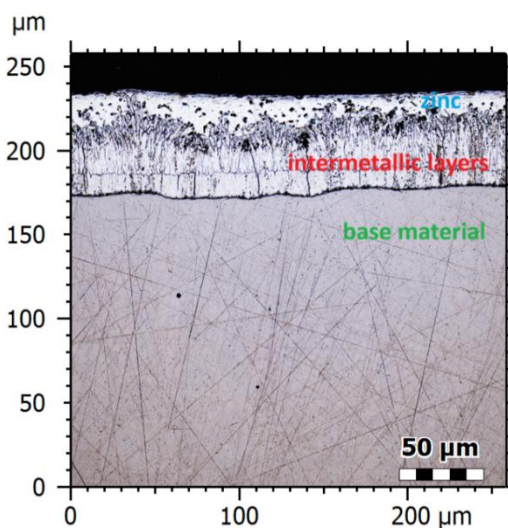
Sample 1: flat sample, uncooled, unswept



Sample 2: flat sample, cooled, unswept



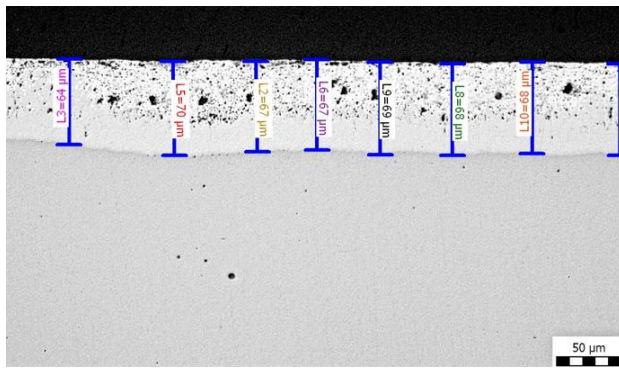
Sample 3: flat sample, uncooled, swept



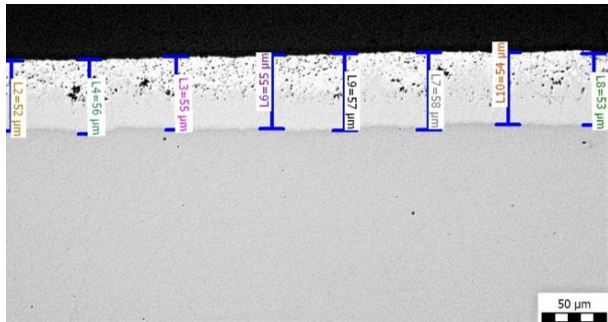
Sample 4: flat sample, cooled, swept

Figure 9. Metallographic analysis flat samples

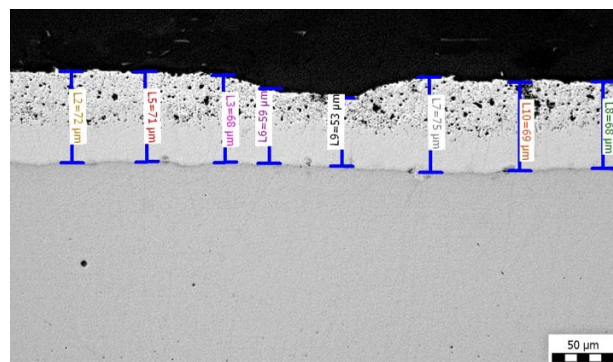
Figure 10 shows the measured values of zinc and intermetallic layers of flat samples. For clarity, a graphical representation of the measured values is provided below.



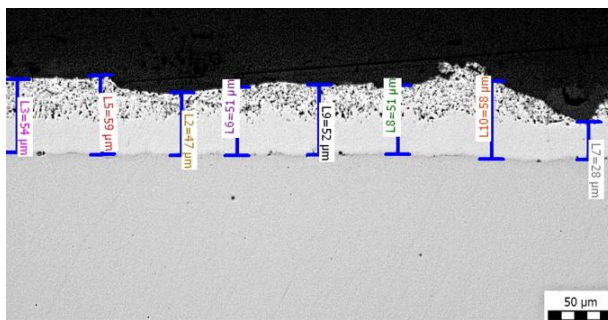
Sample 1: flat sample, uncooled, unswept



Sample 2: flat sample, cooled, unswept



Sample 3: flat sample, uncooled, swept



Sample 4: flat sample, cooled, swept

Figure 10. Measurement of layer thickness in flat samples

Figure 11 graphically shows the measured average thicknesses of the zinc and intermetallic layers of individual flat samples. It is evident that cooled samples have lower thickness than uncooled samples.

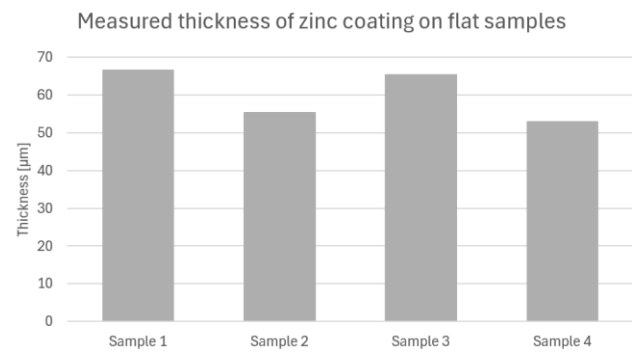
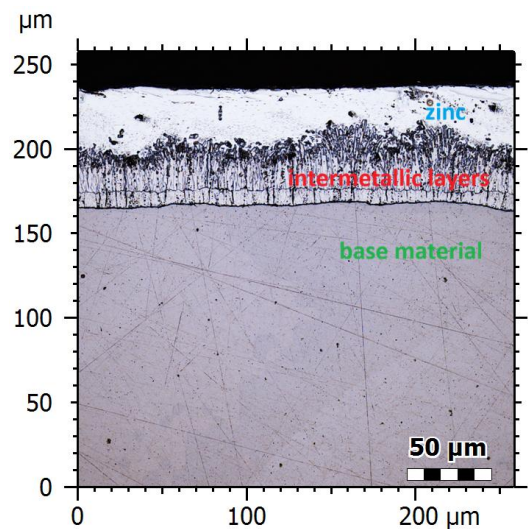
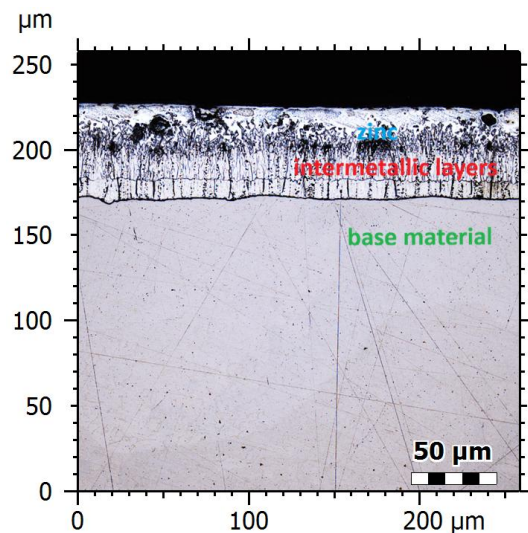


Figure 11. Measurement of layer thickness in flat samples

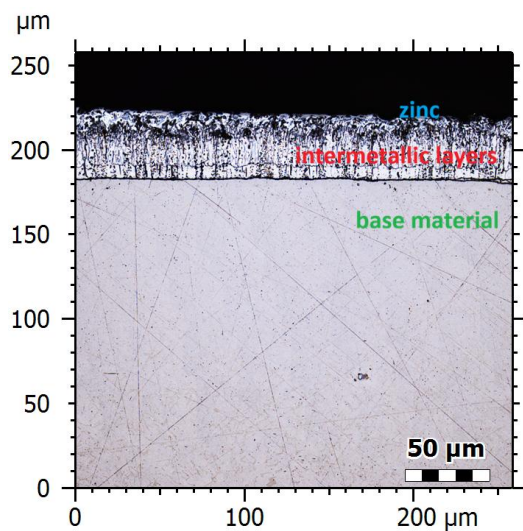
Figure 12 below shows individual cross-sections of the pipes. The figures show the distribution of zinc and intermetallic layers. Figure 13 shows the measured values of the zinc layers of the pipes. Once again, there is a visible difference in the uniformity of the zinc layer between the non-swept samples (samples 1 and 2) and the swept samples (samples 3 and 4).



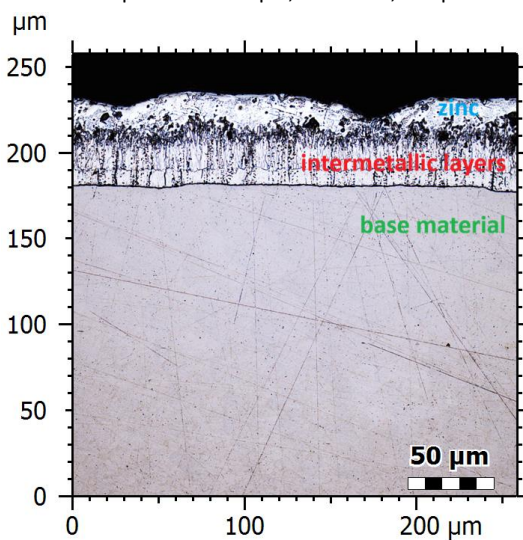
Sample 1: flat sample, uncooled, unswept



Sample 2: flat sample, cooled, unswept



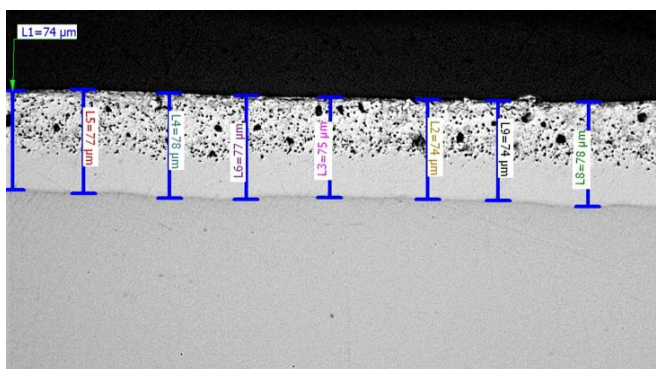
Sample 3: flat sample, uncooled, swept



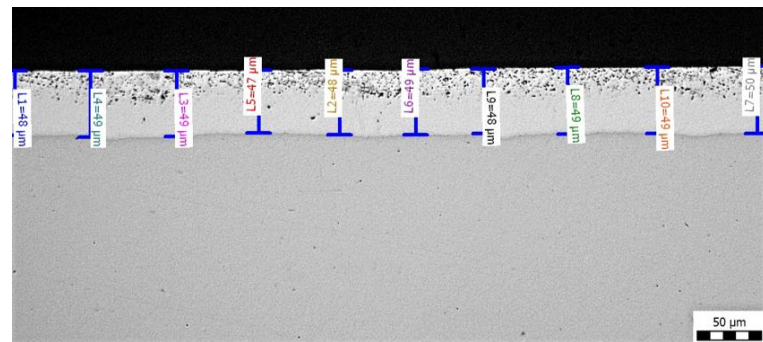
Sample 4: flat sample, cooled, swept

Figure 12. Measuring the thickness of pipe layers

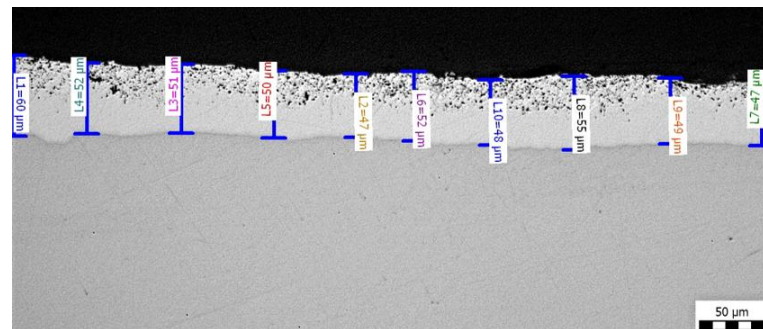
Figure 13 graphically shows the measured average thicknesses of the zinc and intermetallic layers of individual tubes. Sample 1 – uncooled and unswept – had the thickest layer. Cooled samples show lower thickness than uncooled samples due to the limited growth of brittle intermetallic phases.



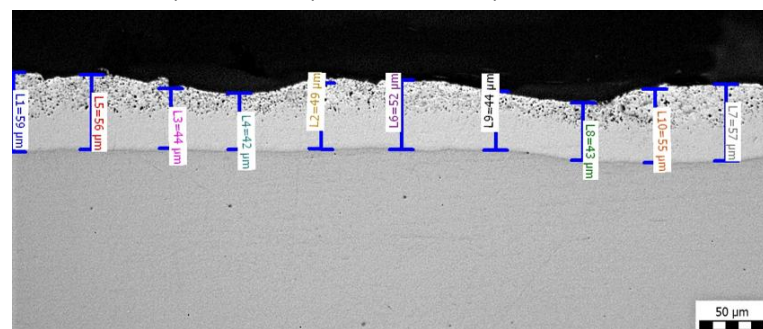
Sample 1: flat sample, uncooled, unswept



Sample 2: flat sample, cooled, unswept



Sample 3: flat sample, uncooled, swept



Sample 4: flat sample, cooled, swept

Figure 13. Measuring the thickness of pipe layer

Figure 14 graphically shows the measured average thicknesses of the zinc and intermetallic layers of individual tubes. Sample 1 – uncooled and unswept – had the thickest layer.

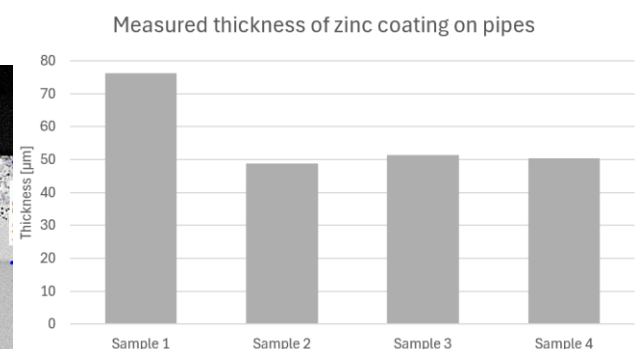


Figure 14. Measuring the thickness of pipe layer

4 CONCLUSIONS

The experimental results presented in this study confirm the significant influence of the cooling method on the course of diffusion reactions and the resulting thickness of the zinc coating. The application of rapid cooling effectively limits the growth of brittle intermetallic phases, whose excessive development would lead to a dull appearance of the coating.

Based on the results of the bending test and the crush test, it can be concluded that hot-dip galvanized coatings showed a high level of cohesion in all cases, even under mechanical loads significantly exceeding normal operating conditions. In the case of tubular samples, slightly better adhesion was observed in the variants subjected to cooling, while in the case of flat samples, better results were achieved by samples without additional cooling. Given that the applied level of plastic deformation significantly exceeds real operating stresses and that tubular and flat samples show opposite tendencies, this method cannot clearly confirm a significant influence of the cooling regime on the adhesion of the zinc coating under mechanical stress. However, the test clearly demonstrated the high resistance and integrity of the coating regardless of the cooling method.

Metallographic analysis did not reveal any defects or flaws in the coating structure, such as porosity or cracks. The zinc coating exhibited a high level of cohesion and adhesion to the steel substrate, which was also confirmed by the results of the pull-off test. The variability in coating thickness in the analysed range, influenced by the cooling regime and sweeping process used, had no significant impact on the mechanical properties of the samples examined.

Based on the test methods performed, no significant negative effect of cooling after galvanizing on the adhesion of the coating during the sweeping process was confirmed. A more likely factor affecting the loss of adhesion appears to be non-compliance with the prescribed technological parameters of sweeping, in particular the blasting pressure, the angle of impact of the abrasive, or the choice of abrasive used. The prevention of these defects can therefore be ensured primarily by strict adherence to the specified technological conditions. To verify this hypothesis, it would be appropriate to conduct additional experiments involving a systematic analysis of the influence of individual sweeping parameters.

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entitled "Research and Development of Technologies for Mechanical Engineering and Production Management" carried out in 2025 at the Faculty of Mechanical Engineering, VŠB – Technical University of Ostrava.

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