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THE APPLICATION OF AN ARTIFICIAL NEURAL NETWORK FOR DETERMINING THE INFLUENCE OF THE PARAMETERS FOR THE DEPOSITION OF A ZINC COATING ON STEEL TUBES

UPORABA UMETNIH NEVRONSKIH MREŽ ZA DOLOČITEV DEBELINE CINKOVE PLASTI NA JEKLENIH CEVEH

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The influence of deposition temperature and time on the thickness of a zinc coating on tubes with different dimensions was investigated. Backpropagation neural networks (BPNNs) were established to predict the zinc-coating thickness on the tubes using the temperature of the zinc melt, the deposition time and the tube diameter as the inputs. A BPNN was used to determine the optimal temperature range for zinc deposition on tubes with a diameter of 48.3 mm and determine the influence of the deposition time on the zinc-coating thickness.

Key words: zinc-coating deposition, temperature, coating thickness, artificial neural networks

Povratna nevronska mreža (BPNM) je bila uporabljena za oceno debeline plasti cinka na podlagi temperature cinkove kopeli, trajanja cinkanja in premera cevi kot vstopnih podatkov. Z mrežo BPNM je bilo določeno optimalno temperaturno področje za cinkanje cevi s premerom 48,3 mm in vpliv trajanja cinkanja na debelino cinkove plasti.

Ključne besede: cinkanje cevi, temperatura, debelina cinkove plasti, umetne nevronske mreže

1 INTRODUCTION

Zinc deposition is the most efficient and ecologically most acceptable method of protecting steel from corrosion. Because of the high affinity of zinc for oxygen, in the presence of moisture and carbon oxide in the atmosphere, the outer layer of the zinc is changed to alkaline zinc carbonate, a layer (known as "white rust") that prevents any advance of the corrosion process. In comparison to other corrosion-protection methods, zinc deposition provides long-term protection (20–50 years), the process is automated and fast, the protective layer is resistant to mechanical damage, the protection of complex shapes is possible and a uniform thickness of the protective layer is achieved.

In the last few years the demand for zinc-coated tubes has increased significantly. Today, more than 75.0 % of the tubes produced use some sort of corrosion protection. For certain types and applications of tubes, the minimum thickness of the zinc coating is defined in standards. However, the price of zinc is high and increasing the thickness of the zinc coating significantly increases the production costs. The zinc metal costs amount to approximately 50.0 % of the costs of the deposition process.

Zinc deposition is a very complex process [1,2]. Molten zinc in contact with steel forms alloys, which have different compositions (different phases). Some of them are brittle and are detrimental to the quality of the zinc coating. The zinc-coating thickness depends on several factors: the temperature of the molten-zinc bath, the deposition (immersion) time and the chemical composition of the steel [3,4]. The process of forming the zinc coating by reacting the zinc with iron is influenced by carbon, phosphorus, silicon and aluminum. Carbon, phosphorus and silicon have a significant, negative influence on the quality of the zinc coating; they promote the formation of brittle phases that cause peeling of the zinc coating from the pipe [3].

The melting point of zinc is 419.4 °C and the deposition process is carried out in the temperature range from 430 °C to 460 °C. After immersion of the tubes the zinc-melt temperature decreases, and it must not fall below 430 °C. At higher temperatures the thickness of the zinc coating increases and the share of the brittle phases in the coating rapidly increases, also [1,3].

The deposition time depends on the mass of the tube and must be equal to the time needed to equalize the temperature of the tube and of the zinc bath. If the immersion time is shorter, the zinc coating will be thick and the surface of the tube will be rough because of the crystallization of the zinc on the colder tube surface. If the immersion time is too long, the zinc coating will be brittle, see also [1–4]. The angle of the tube extraction from the zinc bath affects both the zinc-coating thickness and its appearance. By increasing the angle of extraction, the draining of the zinc from the surface of the tubes increases and the thickness of the zinc coating is reduced [3]. The temperature of the zinc bath is a very significant parameter with regard to the zinc-coating thickness. Thus, it is clear that determining the optimal process parameters to obtain the desired zinc-coating thickness is of great importance.

Based on its characteristics, the deposition of a zinc coating from a zinc bath, as with most technical processes, belongs to the group of complex and nonlinear systems. This means that the temperature of the zinc melt (i.e., the bath), the dependence of the immersion time and the thickness of the zinc coating on the tubes is not linear. Models that describe this system based on a multiple linear-regression technique could be applied more or less successfully, but only for specific process conditions under which they have been developed.

2 APPLICATION OF THE NEURAL NETWORK

In recent years, rapid progress in artificial intelligence has enabled us to use a new method for processing information – artificial neural networks (ANNs) (5). ANNs are complex systems consisting of simple elements (artificial neurons) operating in parallel, which can successfully solve the system's nonlinearity. These elements (neurons), inspired by biological nervous systems, are in a specific interaction, mutually and with the environment of the system (the weights of the artificial neural networks), in this way building a functional unit. Two or more neurons may be combined in a layer, and a particular network might contain one or more layers (input layers, output layers and hidden layers, also). The number of inputs to the network is determined by the problem and the number of neurons in the output layer is defined by the number of outputs required by the problem. However, the designer has to define the number of layers between the network input and the output layer and the size of the layers (the number of neurons).

The network function is determined by the connections between the elements. We can train (i.e., teach) the ANN to perform a particular function by adjusting the values of the connections (i.e., the weights) between the elements. Each input to the neuron is weighted with an appropriate weight. The sum of the weighted inputs and the bias forms the input to the neuron transfer function, which maps a neuron's (or layer's) net output to its actual output. The most popular transfer functions are linear, log sigmoid, hyperbolic, tangent, sigmoid, etc. The bias is much like the weight, except that it has a constant input of 1.

A properly trained ANN can map input to output patterns with minimal error between the modeled and the measured output values. The testing of an ANN follows its training and it is performed with a new input data set, which is not included in the input data set for training the ANN.

Currently, backpropagation is the most important and the most widely used algorithm for neural network training. This algorithm uses the mean squared error and the gradient descent for training.

The goal of these examinations was to determine the influence of the immersion parameters, in the first place the influence of the zinc-bath temperature and the immersion time on the zinc-coating thickness and establish neural network models for predicting of the zinc-coating thickness using the deposition parameters as the inputs.

3 EXPERIMENTAL

The information that the zinc-coating thickness on the tubes was much greater than that prescribed in the EN10240 standard was confirmed in a preliminary study [6]. In the frame of this study the thickness of the zinc coating was assessed for six different tube dimensions and a larger number of samples.

The technological process of the zinc deposition on the tubes consists of a chemical treatment, drying, zinc deposition, removal of the excess zinc and cooling. The tubes are immersed in a standard detergent suspension for 10 minutes, washed out in water with two to three immersions in an inclined position for draining the detergent and pickled in (50 g/L) sulphuric acid at 65 °C for 20 min. Then the tubes are rinsed three times and treated with suspensions of $ZnCl_2$ (155–185 g/L) and NH_4Cl (180–200 g/L) and finally dried at 120 °C and coated.

The chemical composition of the zinc bath was controlled and maintained in the prescribed range. The temperature of the bath was only changed during the process if required by the processing, for example, a change of the tube dimensions or the coating thickness, a standstill of the coating line, etc. The immersion time was selected with regard to the tube dimensions and then varied to determine its influence on the zinc-coating thickness. After the zinc deposition, the excess zinc from the tubes was removed with compressed air at a pressure of 2 bar and cooled in water. Also, on rejected tubes the coating thickness was not assessed for the collection of the required data. The tubes' assessment data are shown in **Table 1**.

Table 1: Overview of the performed measurements
Tabela 1: Pregled opravljenih meritev

Tube diameter, mm	Immersion time, s	Number of measurements	Temperature, °C		Zinc-coating thickness, g/m^2	
			min.	max.	min.	max.
26.9	10.63	132	437	452	415	599
33.4	10.35	85	435	462	463	649
42.4	8.80	111	445	454	429	649
48.3	7.72	150	449	568	414	680
60.3	5.63	66	445	460	454	689
71.6	4.25	57	450	661	420	569

All the assessments were performed in real industrial conditions on a quantity of 3830 t of coated tubes of six different diameters. A total of 601 measurements of the zinc-deposition temperature and the zinc-coating thickness were performed.

4 RESULTS AND DISCUSSION

In the first phase of the examination all the measured data were used to create the ANN (all the tubes' diameters together) and the performance of the ANN in predicting the thickness of the zinc coating on tubes was checked with the coefficient correlation (R). The input parameters for the ANN were the tube diameter, the zinc-bath temperature and the deposition time, and the output parameter was the thickness of the zinc coating. When creating a neural network, it is important to prevent any overfitting of the data. In this work, the early-stopping method was used to improve the network generalization and prevent the overfitting. According to this method, the experimental data set is divided into three subsets: the training data set, the validation data set and the test data set. The training data set was used for computing the gradient and updating the network's weights and biases. The validation data set was not included in the training data set and was used to decide when to stop the training. The test data set error was not used during the training; it was, however, used for the comparison of the different models, i.e., for the evaluation of the performance of the networks. To achieve the most efficient training, the input and the output data are normalized before the training.

In this paper, different network architectures are examined, with the aim to determine the networks with the minimal generalization error. The best results were achieved with the multilayer backpropagation neural networks (BPNNs) trained using the Levenberg-Marquardt algorithm.

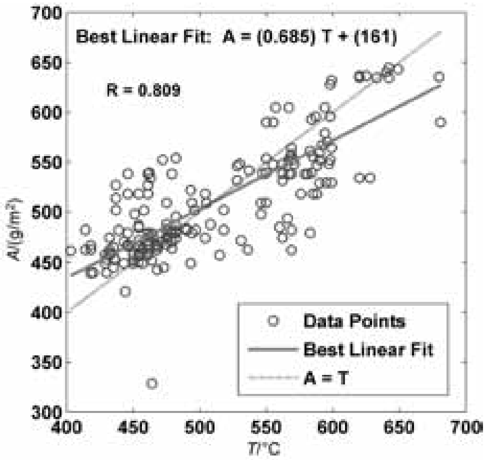

Figure 1: Performance of the BPNN for the test data set. *R* – coefficient correlation, *A* – predicted values of zinc-coating thickness (g/m^2), *T* – target values of zinc-coating thickness (g/m^2). All tested tubes together

Slika 1: Performance BPNN za sklop podatkov: *R* – koeficient korelacije, *A* – napovedane debeline cinkove plasti (g/m^2), *T* – ciljne debeline cinkove plasti (g/m^2), vse cevi skupaj

The performances of the trained BPNNs were determined with regression analysis of the networks' outputs (predicted values of the zinc coating) and the corresponding target values of the zinc coating were obtained experimentally (**Table 2**). **Figure 1** shows the performance of the BPNN on the test data set.

Table 2: Coefficients' correlation (*R*) for training, validation, tests and the entire data set (all diameters of the tubes together)

Tabela 2: Koeficienti korelacije (*R*) za trening, preverjanje in preizkuse ter pregled vseh podatkov (za vse cevi)

Data set	Training data set	Validation data set	Test data set	Entire data set
R	0.823	0.828	0.809	0.821

Figure 1 shows a good network generalization, which is confirmed by a high value of the coefficients' correlation between the networks' outputs and the corresponding target measured values, confirming the correctness of the network architecture and the proper selection of the input network parameters.

With the goal of achieving a higher accuracy of prediction of the zinc-coating thickness, a separate neural network was established for each tube diameter. The input parameters for the ANN were the temperature of the zinc melt and the immersion time, and the output parameter was the zinc-coating thickness. The early-stopping method was used to improve the network generalization and prevent the overfitting. To achieve the most efficient training, the input and the output data were normalized before the training.

Different networks' architectures were examined to determine the networks with a minimal generalization error. The best results were achieved with the multilayer backpropagation neural networks (BPNNs) trained using the Levenberg-Marquardt algorithm.

The performances of the trained BPNNs were checked with regression analyses between the networks' outputs (predicted values of zinc coating) and the corresponding target values of the zinc coating obtained with the measurements (**Table 3**). **Figure 2** shows the performance of the BPNN on the test data set for each tube diameter.

Figure 2 shows the good networks' generalization, confirmed by high values of the coefficients' correlation between the networks' outputs and the corresponding target values obtained by measuring (from 0.759 for smallest diameter tubes (26.9 mm) to 0.947 for tubes with a diameter of 60.3 mm). The correlation confirms the correctness of the networks' architectures and the proper selection of input networks' parameters.

Tubes with diameter of 48.3 mm represent the majority of the zinc-coated product. For this reason, the largest number of measurements (150 cases) was carried out on tubes of this diameter (**Table 1**). In **Table 4** some measurements are shown.

Table 3: Coefficients' correlation (*R*) for training, validation and test, and the entire data set

Tabela 3: Koeficienti korelacije (*R*) za trening, preverjanje in preizkuse

Tube diameter, mm	BPNN label	Coefficient correlation, *R*			
		Training data set	Validation data set	Test data set	Entire data set
26.9	BPNN1	0.727	0.741	0.844	0.759
33.4	BPNN2	0.857	0.896	0.904	0.878
42.4	BPNN3	0.803	0.802	0.767	0.802
48.3	BPNN4	0.872	0.858	0.871	0.868
60.3	BPNN5	0.967	0.902	0.952	0.947
71.6	BPNN6	0.806	0.948	0.905	0.864

The high coefficients' correlation between the network outputs and the corresponding target values obtained with the measurements ($R = 0.868$) confirms

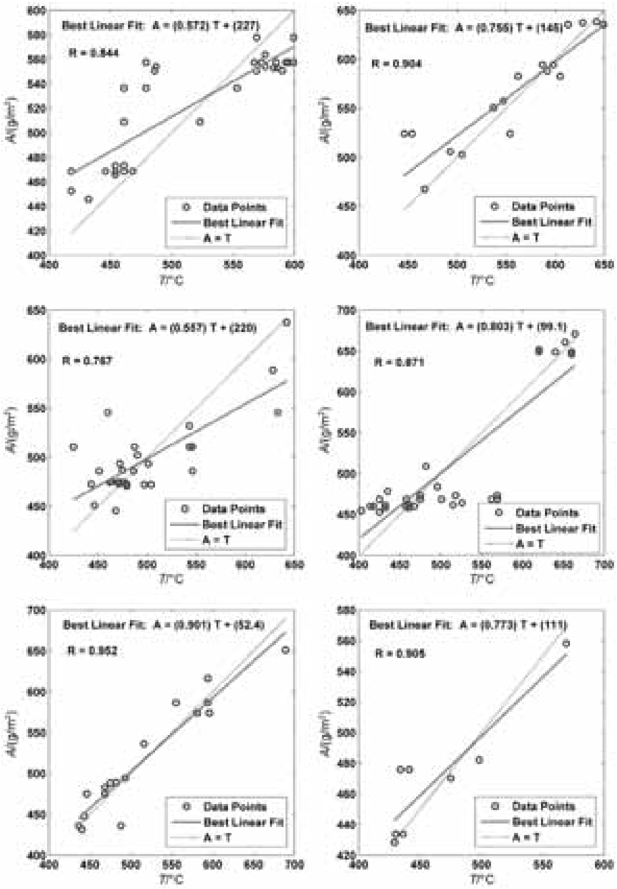

Figure 2: Performance of the BPNN on the test data set for tubes of different diameters: a) 26.9 mm (BPNN1), b) 33.4 mm (BPNN2), c) 42.4 mm (BPNN3), d) 48.3 mm (BPNN4), e) 60.3 mm (BPNN5), f) 71.6 mm (BPNN6). *R* – coefficient of correlation, *A* – predicted zinc-coating thickness (g/m^2), *T* – target zinc-coating thickness (g/m^2)

Slika 2: Performance BPNN za sklop podatkov za cevi z različnim premerom: a) 26.9 mm, b) 33,4 mm, d) 48,3 mm, e) 60,3 mm, f) 71,6 mm. *R* – koeficienrt korelacije, *A* – napovedana debelina plasti cinka (g/m^2), *T* – ciljna debelina plasti cinka (g/m^2)

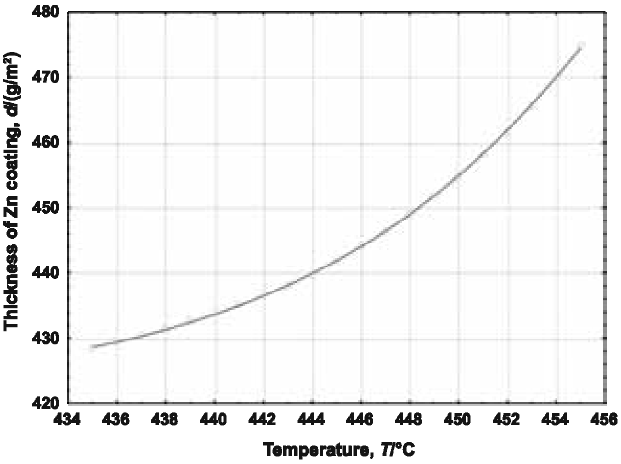

Figure 3: Dependence of zinc-coating thickness on zinc-melt temperature. Immersion time: 84.0 s. Tube diameter: 48.3 mm. Results obtained with BPNN4.

Slika 3: Odvisnost med debelino cinkove plasti *d* in temperaturo taline; čas v kopeli 84 s, premer cevi 48,3 mm. Rezultati BPNN4.

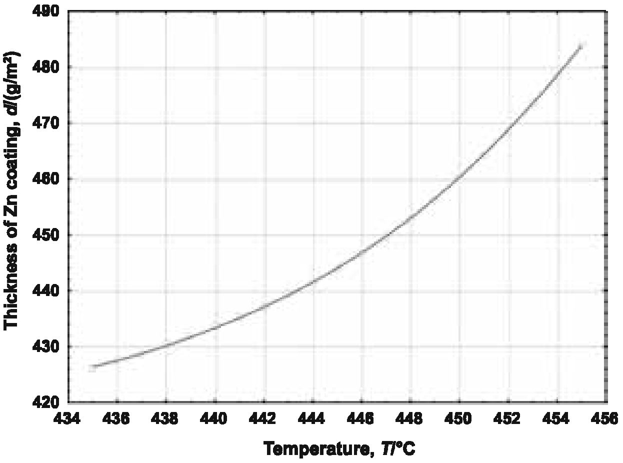

Figure 4: Dependence of zinc-coating thickness on zinc-melt temperature. Immersion time: 92.0 s. Tube diameter: 48.3 mm. Results obtained by BPNN4.

Slika 4: Odvisnost med debelino plasti cinka *d* in temperaturo kopeli; čas v kopeli 92 s, premer cevi 48,3 mm. Rezultati BPNN4.

Table 4: Measured values of the zinc-deposition parameters and the zinc-coating thickness (tubes of diameter 48.3 mm)

Tabela 4: Izmerjeni parametri za nanos cinka in debelina plasti cinka (cevi s premerom 48,3 mm)

Ordinal number	Immersion time, s	Temperature of zinc melt, °C	Zinc-coating thickness, g/m^2
1	84.0	446	398
2		455	625
3		450	418
4		460	652
5		459	482
…	…	…	…
145	92.0	448	525
146		455	536
148		450	475
149		460	524
150		453	569

the suitability of the networks' architecture. The optimal deposition temperature was obtained for this tube diameter (48.3 mm) with an ANN for both immersion times of 84.0 s and 92.0 s (figures 3 and 4). The zinc-melt temperature was varied in the interval from 430 °C to 456 °C for both immersion times.

According to the norm EN10240, the minimum thickness of the zinc coating on the tube (the mass of zinc coating per unit of surface) is 400 g/m^2. In **Figures 3 and 4** it is shown that the optimal temperature interval for coating tubes with a diameter of 48.3 mm is 430–440 °C. In this temperature interval the immersion time did not have an important influence on the thickness of the zinc coating. The obtained results show that it is also possible to decrease the immersion time.

5 CONCLUSIONS

- the investigation shows that it is possible to determine the influence of the deposition parameters on the thickness of the zinc coating and optimize the coating by applying the artificial neural networks;
- different network architectures were examined to determine the networks with a minimum generalization error. The best results were achieved by applying the multilayer backpropagation neural networks (BPNNs) trained using the Levenberg-Marquardt algorithm;
- high values of the coefficients' correlation between the networks' outputs and the corresponding target values obtained by measuring show a good networks' generalization for all the tube dimensions, all together and for each tube dimension separately;
- for most of the tube stock produced, a tube of diameter 48.3 mm, the dependence of the deposition temperature and the zinc-coating thickness were obtained. The optimal temperature range for the zinc deposition on these tubes was 430–440 °C;
- additionally, it was found that the used immersion time at the lower galvanization temperatures did not have a significant influence on the zinc-coating thickness, while at the temperatures above 442 °C, with an increase in the immersion time the zinc-coating thickness was increased too.

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