Journal of Casting & Materials Engineering Vol. 8 No. 3 (2024) 45–53
https://doi.org/10.7494/jcme.2024.8.3.45

Alloys for Hot Dip Galvanising on Thin-Walled Materials

Piotr Lewartowski[a, b], Beata Leszczyńska-Madej[a], Grzegorz Włoch[a], Piotr Żabiński[a]

[a]AGH University of Krakow, Mickiewicza 30, 30-059 Krakow, Poland
[b]DK Innowacje "Ocynkownia" Wężerów 124, 32-090 Słomniki, Poland
e-mail: zabinski@agh.edu.pl

Received: 27 June 2024/Accepted: 30 September 2024/Published online: 23 October 2024.
This article is published with open access at AGH University of Science and Technology Journals.

Abstract

The article reviews alloy additives to zinc and their impact on the quality of coatings achieved on structural steel. It also analyses the impact of the concentration of acid used for the chemical stripping of raw material on the zinc coating thickness of the steel. The zinc layer thickness changed depending on the concentration of alloy elements in the bath. It was stated that aluminium and bismuth have a low impact on the decrease in zinc coating thickness, while in the case of tin, a small change to the content (from 0.6% to 0.8%) significantly decreased the zinc layer thickness. Furthermore, it was found that, during the hot dip galvanising of steel, particular alloy elements are extracted from the bath. This results in the need to supplement alloy elements through periodical melting in for the purpose of maintaining the assumed bath composition. It was observed that, together with the increase in alloy elements concentration, zinc uptake (galvanised component weight ratio to black component weight) decreases, improving the process economics.

Keywords:
zinc, hot deep galvanizing, thin walled element

1. INTRODUCTION

1.1. Global zinc market

Every year, about 12 million Mg of zinc are mined globally. For example, approximately 12.8 million Mg of zinc were mined in 2021. It is estimated that global zinc mining will grow in the coming years, achieving the level of approximately 13.9 million Mg in 2025. The main zinc producers principally include China, as well as Peru and Australia. Annual zinc mining in those countries in 2021 achieved the levels of 4.2, 1.6, and 1.3 million Mg, respectively. Furthermore, top producers of zinc include India, Mexico, USA, and Bolivia. Zinc ore is also mined in Poland, mainly in the southern part of the country, near Olkusz and Chrzanów [1].

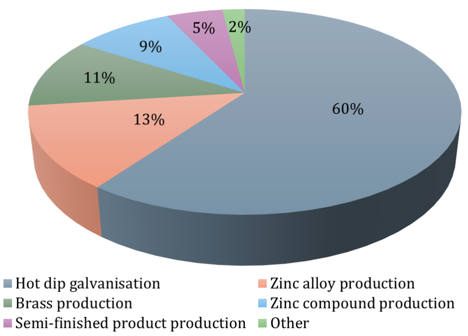

Fig. 1. Zinc consumption in various sectors of the economy. Source: developed pursuant to [2]

Zinc is predominantly used for the hot dip galvanising of steel products. Other important sectors using zinc include brass production, as well as the zinc alloy production industry. Furthermore, zinc is used in production of inorganic zinc compounds and semi-finished products such as rubber, batteries, roof coatings, and others. Figure 1 illustrates the percentage use of zinc in particular sectors.

1.2. Development of the galvanisation market in Poland in the mid-20th century

Figure 2 presents the volume of galvanised structures in Poland in the years 2010–2017.

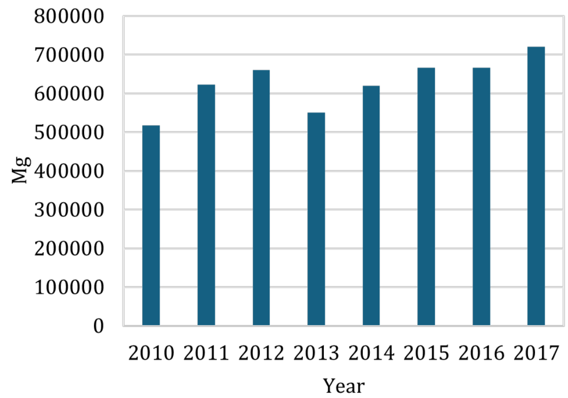

Fig. 2. Volume of galvanised material in the period 2010–2017

One can perceive the increase in the tonnage of galvanised structures in the last decade. This is also related to numerous economic factors which include the programme of constructing express roads and motorways in Poland, the establishment of many distribution centres with buildings containing steel structures, or the increase in the construction of buildings. These are just a few of the many factors resulting in the increased demand for steel with higher resistance to corrosion.

Based on the assessment of the current situation, one can clearly state that the galvanisation market in Poland is gradually developing. In the 1960s, the first large galvanisation plants were built in Krakow, as well as Inowrocław. Currently, there are over 50 galvanisation plants in Poland, predominantly located in the southern and central part of the country. The main factors affecting the location of most galvanisation plants include existing industrial plants nearby, developed infrastructure, as well as connections to traffic and transport networks. The main factor that differentiates galvanisation plants from one another, however, is the working dimension of the galvanisation bath that affects the dimensions of elements to be galvanised. Furthermore, particular plants continuously strive to develop and extend their offers, among others through having systems for component passivation, or their own powder painting plants.

1.3. The evolution of zinc composition in baths

The first attempts to place zinc coating on a steel element were undertaken in the 18th century. In the first period of using zinc as anticorrosive protection, 'pure zinc' was applied. With the development of this method, experiments began with various admixtures of metallic elements, such as [3]:

– lead:

- chemical element pertaining to heavy metals, soft and malleable,
- reduces surface tension of the alloy, facilitates extraction of hard zinc formed as a result of zinc bath saturation with iron,
- the use of lead also involves negative effects such as, among others, higher possibility of stress corrosion occurrence, and toxicity to the human body;

– aluminium:

- aluminium is a chemical element pertaining to heavy metals and characterised with high plasticity and malleability,
- causes reduced oxidation of the head surface in the zinc bath,
- improves zinc castability, and thus allows to maintain normative zinc coating thickness;

– bismuth:

- chemical element pertaining to heavy metals,
- a brittle metal with silver shine and pink highlight,
- leads to reducing surface tension of zinc bath but with 19-fold higher efficiency than lead, plus it is non-toxic,
- due to higher reactivity with iron, a concentration of 0.1% cannot be exceeded because a higher concentration may result in zinc bath degradation;

– tin:

- chemical element pertaining to heavy metals,
- as an alloying element, tin increases coating shine, and also encourages spangle formation,
- tin improves zinc bath castability causing reduced coating thickness on steels containing silicon in the quantities from 0.035% to 0.25%.

As a result of the high demand for various alloy admixtures based on the diversity of galvanised material, ready zinc alloy mixes were developed [3]:

- ZZA (AL),
- MOD (Al, Sn, Ni),
- Zinc – bright (Bi, Sn),
- ZiNiGal – bright (Ni, Bi, Sn),
- Zinkal 5 / 10 (Al, Cu).

Early in the development process of hot dip galvanising, conventional zinc alloys were used that essentially comprised pure zinc in the volume depending on its 'grade'. This was 'primary zinc.' Chemical compositions of particular primary zinc grades have been provided in DIN EN 1179 [4] and are presented in Table 1.

Table 1
Primary zinc grades and their ingredients

Grade	Colour	Zn content [%]	Maximum mass concentration [%]						Maximum content of elements [%]
			Fe	Cd	Pb	Cu	Sn	Al	
Z1	white	99.995	0.002	0.003	0.003	0.001	0.001	0.001	0.005
Z2	yellow	99.990	0.003	0.003	0.005	0.002	0.001	–	0.010
Z3	green	99.950	0.020	0.005	0.030	0.002	0.001	–	0.050
Z4	blue	99.500	0.050	0.005	0.450	–	–	–	0.500
Z5	black	98.500	0.050	0.005	1.400	–	–	–	1.500

Source: developed pursuant to [4]

Currently in industrial practice, the above zinc types are little used, and they are being replaced by various sorts of zinc alloys with additional alloying elements presented in Table 2.

Table 2
Alloying elements in zinc alloys

Alloying element	Mass concentration [wt.%]	Melting point [°C]	Local coating enrichment [%]
Bi	< 0.1	271	0–6
Sn	< 1.0	231	5–40
Pb	0–1.0	327	0–90
Al	< 0.03	660	$FeAl_3/Fe_2Al_5$
Ni	< 0.06	1453	0.5–1.5
Ti	< 0.3	1727	< 4
V	< 0.05	1919	0.3–2.0

Source: developed pursuant to [3]

During the development of the hot dip galvanising process, lead was one of the first additional alloying elements to be used, principally for technological reasons. First of all, it significantly reduces the surface tension of the alloy [5], as well as facilitating the extraction of hard zinc from the galvanising furnace due to the saturation of the zinc bath with iron. Lead also encourages spangle formation [6]. The impact of lead content on surface tension is presented in Figure 3.

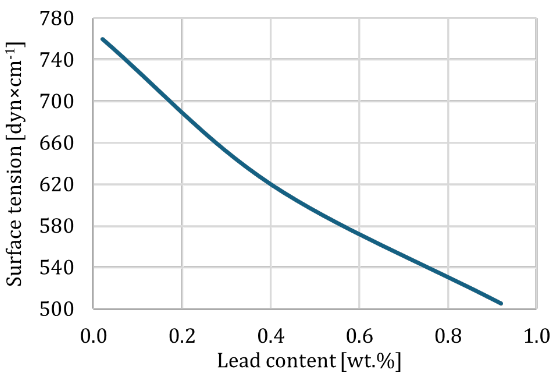

Fig. 3. Change of zinc surface tension depending on Pb content at the temperature of 441°C. Source: developed pursuant to [7]

The use of lead, however, also involves negative effects including the higher possibility of stress corrosion occurrence. Furthermore, lead is toxic to human body. Therefore, attempts were made to replace lead with other alloying elements, principally bismuth. Similarly to the case of lead, bismuth leads to reducing the surface tension of zinc bath but with 19-fold higher efficiency [7], and it is also non-toxic.

Until the 1960s, the galvanisation process exclusively involved alloys containing low additions of aluminium and tin, principally for optical reasons, as well as to obtain thin coating thickness.

The main advantages of using tin as an alloying element include greater shine of the coating, and it also encourages spangle formation [8]. Moreover, tin improves zinc bath castability causing reduced coating thickness on steels containing silicon in the quantities from 0.035% to 0.25% [9].

Nevertheless, the most important alloying element added to the zinc bath is aluminium. It protects the zinc bath surface against quick oxidation due to the formation of a very thin Al_2O_3 film. Moreover, Al contributes to increased bending strength of the coating on the element surface, but principally it increases its shine. Owing to the inhibition of zinc bath oxidation, much lower volume of waste in the form of zinc ashes is generated [7]. It must be pointed out, however, that excessive Al content in the zinc bath (over 0.01%) carries a risk of zinc ashes adhesion to the material surface [3].

With the development of hot dip galvanising technology, nickel started to be used as an alloying element (since 1982). Its quantity should remain within the range of 0.04-0.06% weight. It has been applied for galvanisation of “Sandelina” steel, as well as “Sebisty” steel from the bottom range (up to 0.2% Si).

According to EN ISO 14713-2:2020 [10] “Sandelina” steel is characterised by a silicon content ranging from 0.03% to 0.14%. In the case of galvanised materials produced from this steel grade, their surface does not meet quality requirements. As a result, zinc coating is matt-grey, porous, uneven, very brittle, and sensitive to abrasion, strong deformations, and impacts. “Sandelina” effect causes reduced adhesion of thick coatings to steel, hence it is not recommended to galvanise steel structures containing silicon in the concentration ranges specified above.

According to EN ISO 14713-2:2020 [10] “Sebisty” steel is characterised by a silicon content from 0.14% to 0.25%; in the case of silicon content from the middle of this range, with galvanising temperature increase to 450°C up to the maximum of 470°C, thinner coatings are obtained than at lower temperatures. When galvanising this steel grade, nickel causes reduction to coating thickness, as well as its greater shine. When applying nickel, one must consistently control its concentration in the bath to remain within the aforementioned scope. In the case of insufficient mass concentration, nickel efficiency is rapidly reduced [10]. In turn, in the case where nickel content exceeds 0.06% in weight, losses are generated due to greater pace of its depletion from the zinc bath. Similar properties are observed for titanium and vanadium.

In the period between the 1980s and the 2010s, many attempts were undertaken to add specific alloying elements to the zinc bath. For example, in the United Kingdom, the “Technigalva” alloy was developed and introduced for hot dip galvanising process, characterised with a nickel content at the level of 0.07–0.08%. The Germans also used nickel as an alloying element of zinc bath in their alloys (0.04–0.055%) [11]. In the 1970s, France experimented with “Polygalva” alloy containing additions of aluminium, tin, and magnesium. It allowed a thin, uniform coating to be achieved, with good adhesion both on steels with low and high silicon content [12]. With the development of hot dip galvanising technology, “Galveco” alloy was invented, containing nickel, tin, and bismuth [13]. It was aimed not only at reducing coating thickness, but also at replacing lead with bismuth.

In the coming years, most probably many new and innovative zinc alloys will be invented in response to the growing requirements both in the aspect of technology and economy.

2. METHODOLOGY

Tests were performed on samples of platform gratings galvanised at DK Innowacje Sp. z o.o. – Ocynkownia Wężerów made of steel composed as presented in Table 3. Tests were performed for samples galvanised on 30 March 2022, 5 May 2022, and 10 November 2022. The decisive parameter on sample selection was tin content in the zinc bath.

Samples were analysed using:

- Scanning Electron Microscopy – specification of changes to element composition in particular sample parts (along the thickness);
- Optical Microscopy – specification of produced zinc coating thickness;
- Tribometer (coating wear test) – impact of alloy elements (Al, Sn, Bi) was determined, as contained in the zinc bath, on coating thickness and wear resistance;
- Shimadzu HMV hardness tester – the test results determined the impact of alloy elements on coating hardness.

2.1. Process parameters during sample galvanisation

For each of the samples, the most important galvanisation process parameters were determined, including: stripping acid concentration, zinc temperature and composition, salt content in flux, and other. The mean measured values (3 samples for each date) have been presented in Table 4 and Table 5.
According to the above, we can state that the stripping process of particular samples occurred in similar conditions.

The results reflect the physical-chemical parameters of the processes at which the preparation and galvanisation of the tested samples took place. Slight changes to the parameters can be noticed, which marginally affect coating thickness.

Figures 4–6 present changes to aluminium, tin, and bismuth content in zinc bath applied in DK Innowacje – Ocynkownia Wężerów galvanisation plant.

Periodical supplementation of alloy elements in the bath contributes to the non-linearity of their content. The main problem involved the determination of tin concentration in the bath at the start of the process.

Table 3
Chemical composition of steel used for grating production

Element	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo	V	N	CEV
							[%]						
Min. (norm)	–	–	–	–	–	–	–	–	0.015	–	–	–	–
Max. (norm)	0.120	1.500	0.030	0.025	0.020	–	–	–	–	–	0.200	–	–
Steel	0.040	0.350	0.030	0.010	0.002	0.180	0.060	0.080	0.027	0.010	0.010	–	0.140

Table 4
Stripping acid parameters

Bath parameters	30.03.2022	5.05.2022	10.11.2022
HCl [g/l]	119.5	82.8	142.0
Fe [g/l]	96.5	117.0	89.1
d [g/cm^3]	1.233	1.253	1.216

Table 5
Galvanisation process parameters

Parameter	Value on a given galvanisation date			Unit
	30.03.2022	5.05.2022	10.11.2022	
Zinc temperature	451	450	450	[°C]
Dryer temperature	99	101	100	[°C]
NH_4Cl content in flux	120.1	148.5	123.1	[g/l]
$ZnCl_2$ content in flux	196.4	172.2	179.2	[g/l]
pH of flux	3.4	3.6	3.6	[–]
pH of degreasing solution	13.2	12.6	12.6	[–]
Free alkalinity of degreasing solution	16	14	15	[g/l]
Al content in zinc bath	0.0029	0.017	0.0025	[wt.%]
Fe content in zinc bath	0.0235	0.0263	0.0252	[wt.%]
Sn content in zinc bath	0.6520	0.5840	0.8460	[wt.%]
Bi content in zinc bath	0.0825	0.0764	0.0926	[wt.%]
Ni content in zinc bath	0.0010	0.0006	0.0005	[wt.%]

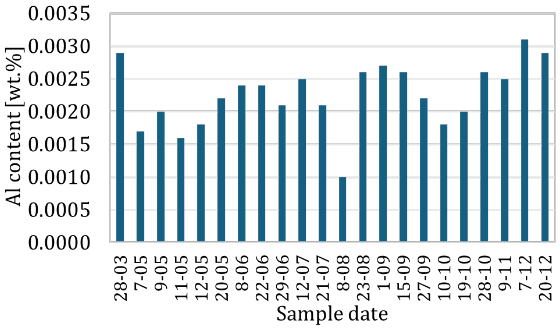

Fig. 4. Changes to aluminium content in zinc bath at the example of DK Ocynkownia

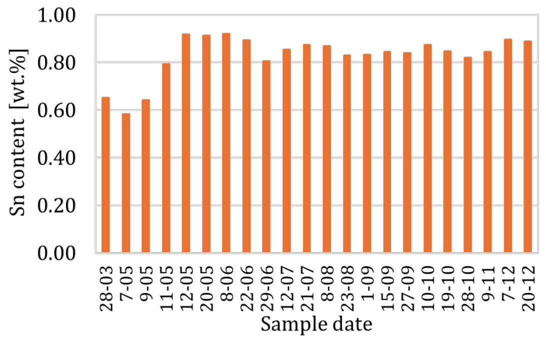

Fig. 5. Changes to tin content in zinc bath at the example of DK Ocynkownia

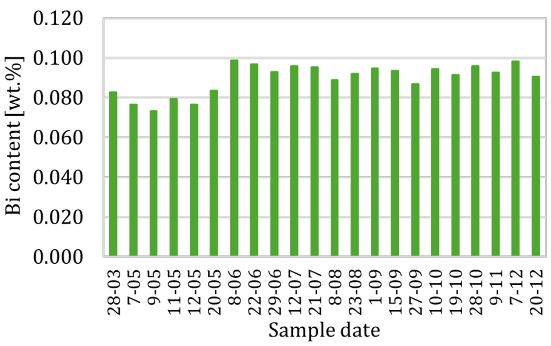

Fig. 6. Changes to bismuth content in zinc bath at the example of DK Ocynkownia

Because the general approach to galvanisation assumes concentration of this element not exceeding 0.6%, our assumptions for zinc coating of materials with a large active surface were that we should start the process with the concentration of approximately 0.6% and adding the element periodically to reach 0.9%. The concept was to reduce the zinc coating and approximation to standard values.

Figure 7 presents the interdependence of the zinc coating thickness obtained on the material and average hydrochloric acid content in the stripping baths.

Below is the diagram of heating etching that reflects the optimum concentration of ferric chloride and hydrochloric acid. The diagram was developed pursuant to tests and the authors' own experience, and it is helpful for the optimum stripping process of steel structures. The optimal stripping curve is presented in Figure 8 (continuous curve). The upper curve refers to extended etching times, while the lower curve defines the limit below which etching is impossible.

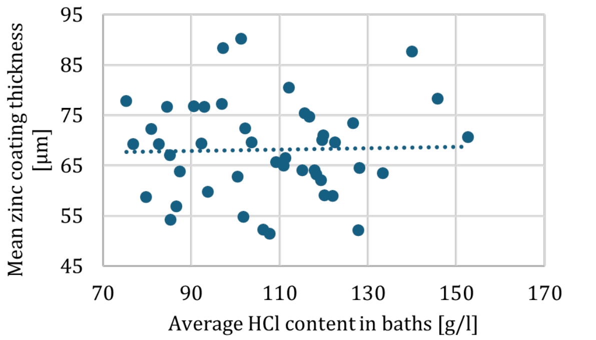

Fig. 7. Dependence of zinc coating thickness on average HCl content in stripping baths

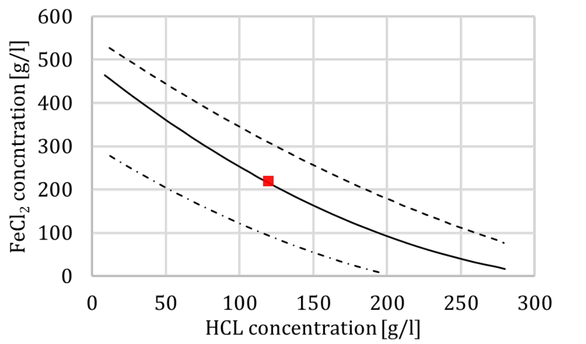

Fig. 8. Optimum stripping curve

2.2. Sample preparation for microscopic tests

From each of the analysed samples, specific fragments were cut out from a larger grid measuring 1 m × 1 m, containing two types of flat bars, namely bearing flat bar and 10 mm × 2 mm flat bar (Fig. 9). Such prepared grating cuts were covered with resin solution, and then left for drying (Fig. 10).

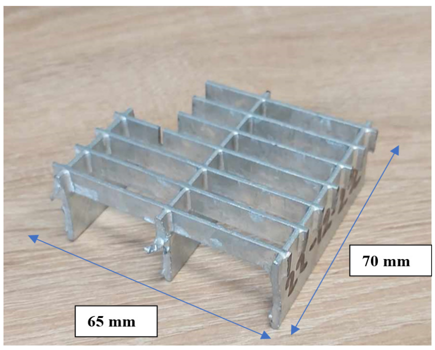

Fig. 9. Fragment of push-in platform grating

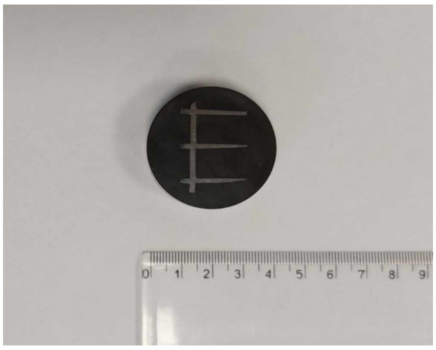

Fig. 10. Sample used for microscopic analysis

2.3. Scanning electron microscopy

In order to determine the element composition of the samples (along the flat bar thickness), the scanning electron microscopy method was applied. Below is an exemplary photo made using electron microscope (Fig. 11) and test results (Figs. 12 and 13). The photo shows a steel substrate with a zinc coating applied.

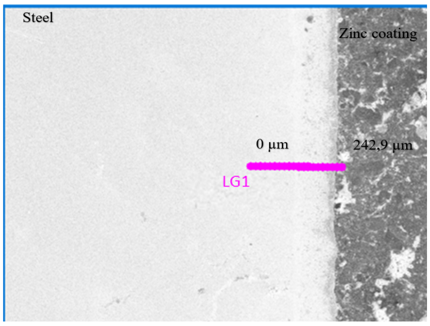

Fig. 11. Photo of a sample made using electron microscope

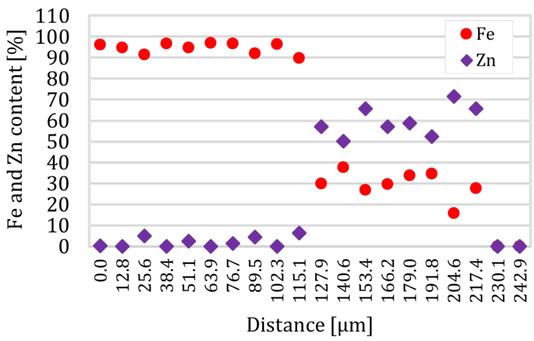

Fig. 12. Iron and zinc content at particular sample parts

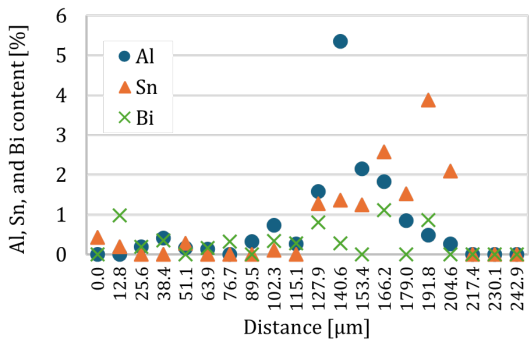

Fig. 13. Aluminium, tin, and bismuth content at particular sample parts

The greatest iron content in the analysed sample is observed in the shim zone and gradually decreases towards the resin area. With respect to zinc, this is different: concentration is nil in the shim zone, it grows in the alloy area and drops down to nil in the resin area.

The greatest accumulation of Al, Sn, and Bi alloy elements is found in the alloy area, and decreases in the area of Fe shim and resin. We can see that during the galvanisation process aluminium, bismuth, and tin are extracted from the bath into the galvanised material. Such a process involves the need to supplement the elements in the bath and this is done periodically alongside zinc addition.

The addition of alloying elements to the bath is extremely important. If the appropriate amounts of alloying elements are not added, it may result in: significant deterioration of the castability of the zinc coating, obtaining coatings of uneven thickness, deterioration of the visual properties of the coating, and others.

2.4. Optical microscopy

In order to determine the thickness of the zinc coating generated on the surface of particular samples, optical microscopy was applied. The analysis involved two types of flat bars forming part of each sample: a bearing flat bar and 10 mm × 2 mm flat bar. Minimum and maximum zinc coating thickness were determined, as well as the mean value.

Figure 14 presents an exemplary photo made using the optical microscope.

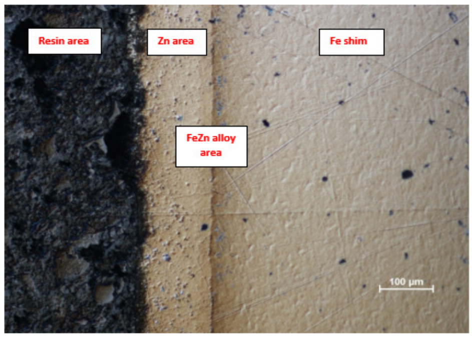

Fig. 14. Photo of a sample made with optical microscope (sample from 30.03.2022)

Tables 6 and 7 present minimum mean zinc coating thickness values according to PN-EN ISO 1461 [14], as well as zinc coating thickness at particular flat bars for each of the samples, determined using the optical microscopy method.

Table 6
Minimum mean zinc coating thickness according to PN-EN ISO 1461 [14]

Material thickness [mm]	Minimum mean zinc coating thickness [µm]
$t > 6$	85
$3 < t \leq 6$	70
$1.5 \leq t \leq 3$	55
$t < 1.5$	45

Table 7
Zinc coating thickness for particular flat bars in three samples

Sample date	Flat bar	Minimum thickness [µm]	Maximum thickness [µm]	Mean thickness [µm]
30.03.2022	10 × 2	87.47	99.56	94.22
	Bearing	61.87	75.38	68.03
05.05.2022	10 × 2	75.38	131.56	102.95
	Bearing	52.62	100.98	78.93
10.11.2022	10 × 2	64.00	91.73	73.88
	Bearing	42.67	54.04	49.70

Table 7 points to significant discrepancies in the zinc coating thickness based on the type of galvanised material. This is caused by the different origin of the base material, since changes to silicon content in steel affects galvanisation quality.

We can notice a reduction to the coating thickness depending on the date of galvanisation (tin content). Evidently, we approximate standard values for such base material thicknesses.

2.5. Al content impact on zinc coating thickness

Changes to the aluminium content in zinc bath applied in DK Innowacje – Ocynkownia Wężerów galvanisation plant were followed (Fig. 15). The impact of Al content in the zinc bath on coating thickness formed on the galvanised grating sample was determined (Fig. 16). Figure 15 indicates that aluminium concentration in the bath changes periodically – it increases to the value of 0.003%, whereas the zinc coating thickness slightly decreases at the same time.

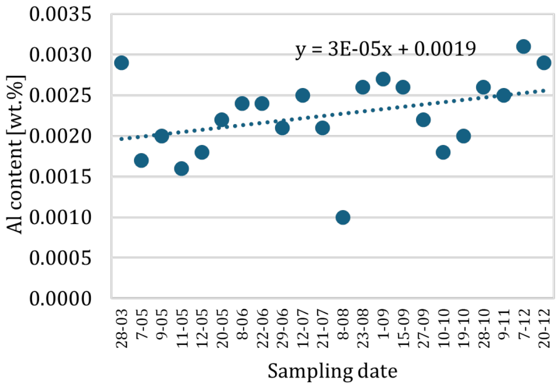

Fig. 15. Changes to aluminium content in the zinc bath

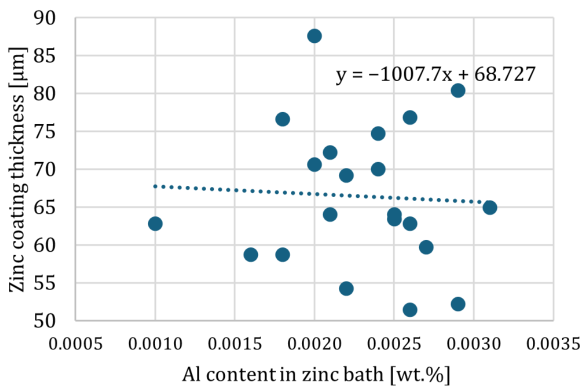

Fig. 16. Impact of aluminium content in the zinc bath on zinc coating thickness

2.6. Bi content impact on zinc coating thickness

Changes to Bi content in zinc bath applied in DK Innowacje – Ocynkownia Wężerów galvanisation plant were followed (Fig. 17). The impact of Bi content in the zinc bath on coating thickness formed on the galvanised grating sample was determined (Fig. 18). Also in the case of bismuth, non-linear change to concentration is observed due to the periodical addition of the element. It has the same small impact on zinc coating thickness as aluminium.

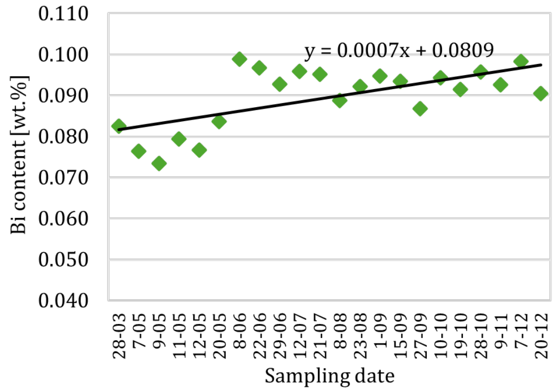

Fig. 17. Changes to bismuth content in the zinc bath

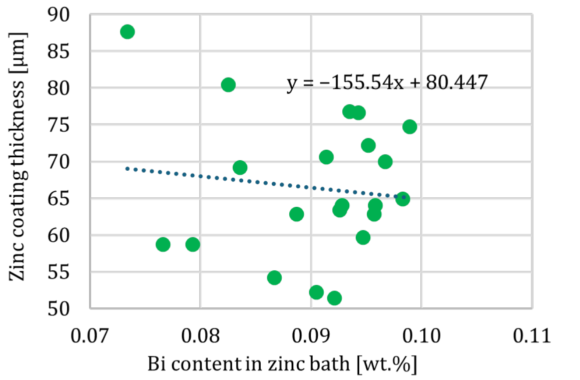

Fig. 18. Impact of bismuth content in the zinc bath on zinc coating thickness

2.7. Sn content impact on zinc coating thickness

Changes to Sn content in the zinc bath applied in DK Innowacje – Ocynkownia Wężerów galvanisation plant were followed (Fig. 19). The impact of Sn content in the zinc bath on coating thickness formed on the galvanised grating sample was determined (Fig. 20). The impact of Sn content in the zinc bath on coating thickness formed on the bearing flat bar and 10 mm × 2 mm flat bar was analysed for the three selected samples (Fig. 21). In the case of tin, a small increase in concentration causes the sudden depletion of the zinc coating. Tin concentration also changes periodically due to non-linear dosage of alloy elements versus their depletion from the zinc bath.

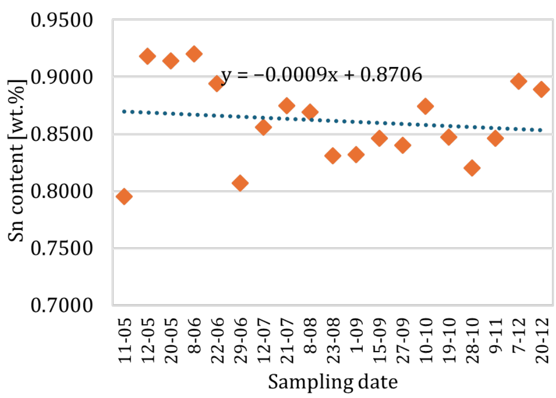

Fig. 19. Changes to tin content in the zinc bath

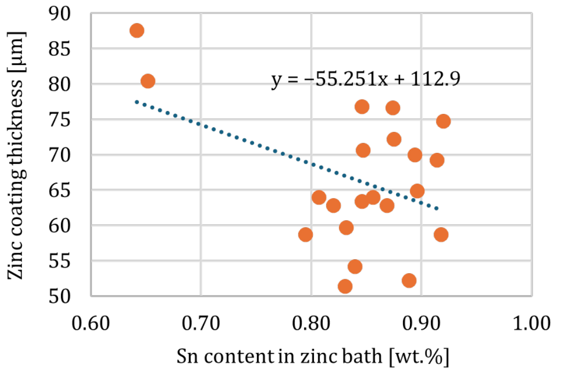

Fig. 20. Impact of tin content in the zinc bath on zinc coating thickness

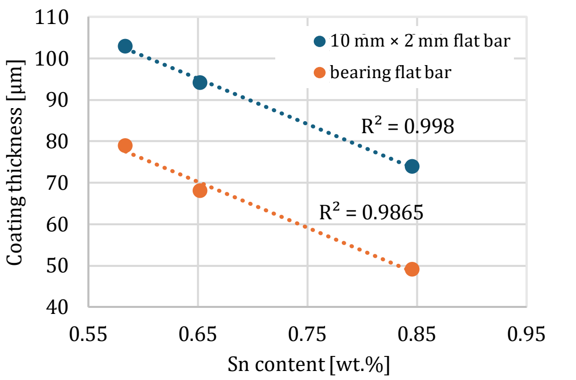

Fig. 21. Impact of tin content in the zinc bath on zinc coating thickness in particular flat bars

Figure 21 presents the impact of tin alloy element concentration on zinc layer thickness. In the figure, one can also notice the differences to coating thickness values depending on the galvanised material. A very high impact on coating thickness can be observed with respect to tin concentration, regardless the type of the galvanised material.

During the galvanizing of steel elements in a zinc bath with alloy additives (Al, Sn, Bi, Ni), it is necessary to maintain their concentration at a relatively constant level. For this purpose, each time subsequent batches of zinc are melted in the galvanizing furnace, appropriate amounts of alloy additives are added.

2.8. Zinc coating wear depending on tin content in the galvanising alloy

Pursuant to the performed analyses, we reached the conclusion that with the increase of alloy element in the form of metallic tin, wear of the zinc coating decreases. This contributes to the longer life of steel components, such as platform gratings or working platforms, and a lower probability of premature wear / degradation of the protective layer. This affects the improved competitiveness of steel components galvanised using this method. Figure 22 presents wear of the zinc coating in time depending on different Sn content in the zinc alloy.

Tribological tests were performed using a T-05 roller-block tribotester. The tests were conducted at an ambient temperature and 40% air humidity, in technically dry friction conditions. Each of the tested material variants was subjected to at least three tribological tests. During the test, a sample measuring 4 mm × 2 mm × 20 mm was mounted in a holder with a hemispherical insert, which ensured the proper contact of the sample with a steel ring rotating at a constant speed.

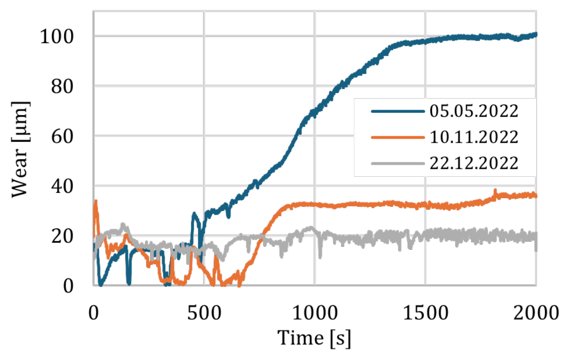

Fig. 22. Wear of zinc coating in time for three samples galvanised using alloy with different tin content

The tribological test parameters were as follows:

- dimensions of tested samples: 20 mm × 2 mm × 4 mm,
- counter sample: hardened steel (100Cr6), 55 HRC, Ø49.5 mm × 8 mm,
- rotation speed: 136 rpm,
- linear speed: 0.25 m/s,
- friction path: 100 and 500 m,
- load: 20 N,
- friction conditions: technically dry friction (without lubrication),
- ambient temperature: 20°C.

In the first samples, the wear was very high, namely the zinc coating completely degraded after approximately 1000 s, whereas with the increase of alloy elements the depletion of zinc coating decreased. In the case of the sample of 22 December 2022, the wear remained at a constant level of approximately 20 µm.

2.9. Zinc coating hardness

To analyse hardness in the zinc coating cross-sections for samples of 5.05.2022, 10.11.2022, and 22.12.2022, 8 hardness measurements were performed for each sample with the load of 0.5 N (0.05 kg) using Shimadzu HMV harness tester. Coating hardness tests were performed in accordance with the standard PN-EN ISO 6507-1:2007 [15].

Table 8 presents measurement results, namely the mean hardness values of the zinc coating. The character "±" presented in the table corresponds to 95% confidence interval.

Table 8
Mean hardness of zinc coating for particular samples

No.	Sample date	Mean hardness [HV]
1	22.12.2022	181±17
2	10.11.2022	153±11
3	05.05.2022	128±15

Steel sheet hardness (sample 10.11.2022) was approximately 252 HV.

Taking into account the hardness values of the zinc coating obtained as a result of hot-dip galvanizing given in the literature: 52 HV [15], 41 HV [16], it can be stated that the average hardness of the zinc coating obtained as a result of the measurements for all three samples is relatively high.

It seems that now the hardness values of such layers differ. As perceived from wear results, coating hardness strongly correlates with the depletion of the zinc coating of the galvanised component. In the cross sections, it was observed that there is one layer first (zinc oxide), followed by a layer with the analysed hardness, and then a steel sheet.

3. CONCLUSION

In the last 30 years, the hot dip galvanisation market has been experiencing rapid development related to the growth of the Polish economy. The observed trends in the sector development are related to the establishment of new industrial centres in Poland (several state-of-the-art galvanisation plants established and to be constructed in the period 2020–2025). Another trend in the development and improved profitability of galvanisation plants involves upgrades and extensions of the existing plants. It was also pointed out that the correct zinc coating of steel structures requires the appropriate preparation of such structures through acid cleaning and degreasing of the surface. Prior knowledge and technical capacities did not account for this process, which shortens the galvanisation time and contributes to greater throughput capacities of plants with similar galvanisation bath sizes. This is also significant for the anticorrosive protection of structures because appropriately prepared surface improves the adhesion of the zinc coating and elongates the anticorrosive protection period.

Pursuant to the analyses and tests performed so far, the following can be stated:

- The application of aluminium (Al) and bismuth (Bi) as alloy additives increases the castability of the zinc alloy and to a small extent decreases the zinc coating thickness.
- Tin (Sn) additive in the range of 0.8–0.9% significantly decreases zinc coating thickness.
- With the above assumption, a significant improvement to zinc coating resistance to wear during operation is observed.

The plant is aware that the Bi content cannot exceed 0.1%, as this increases the possibility of the corrosion of galvanized materials. Additionally, the unusual concentration of tin up to 1% is conditioned by the fact that thin-walled elements (pressed-in gratings) are galvanized in the plant's process. Additionally, these elements are not welded, but pressed-in elements, so there are no overheated places where corrosion centers can occur.

The galvanisation process pursuant to the aforementioned process assumptions results in coatings with appropriate adhesion and causes slightly supra-normative thickness of zinc coating on steel. The aforementioned alloy additives cause an increase to zinc coating hardness and decrease coating sensitivity to wear.

REFERENCES

[1] Malon A., Mikulski S.Z., Oszczepalski S. & Tymiński M. (2013). *Rudy cynku i ołowiu*. Retrieved from: http://surowce-kopalnie.pl/aktualnosc/69 [accessed: 24.06.2024].

[2] *Distribution of zinc consumption worldwide in 2022, by end use.* Retrieved from: https://www.statista.com/statistics/240626/share-of-zinc-consumption-by-category/ [accessed: 25.07.2024].

[3] Schulz W.-D. & Thiele M. (2012). *Feuerverzinken von Stuckgut. Werkstoffe-Technologien-Schichtbildung-Eigenschaften-Fehler*. Bad Saulgau: Eugen G. Leuze Verlag KG.

[4] European Committee for Standardization (2003). *EN 1179 – Zinc and zinc alloys – Primary zinc*.

[5] Krepski R.P. (1985). The influence of lead in after-fabrication hot dip galvanizing. *Proceedings of 14th International Galvanizing Conference*. London: Zinc Development Association, pp. 6/6–6/12.

[6] Borhan-Tavakoli A. (1984). Formation and growth of the Delta 1 phase in Fe-Zn system*. Zeitschrift für Metallkunde*, 75(6), 436–439.

[7] Liberski P. (2013). *Antykorozyjne powłoki zanurzeniowe.* Gliwice: Wydawnictwo Politechniki Śląskiej.

[8] Radeker W. & Friehe W. (1964). Bath alloy additives and their impact on the quality of the galvanized coating. *Proceedings of 7th International Conference on Hot Dip Galvanizing, June 15–19. Paris.* Paris: Pergamon Press, pp. 167–178.

[9] Kania H. & Liberski P. (2008). Struktura i kinetyka wzrostu zanurzeniowych powłok cynkowych otrzymywanych w kąpielach z dodatkiem cyny. *Inżynieria Materiałowa*, 3, 149–153.

[10] EN ISO 14713-2:2020 – Zinc coatings – Guidelines and recommendations for the protection against of iron and steel in structures – Part 2: Hot dip galvanizing.

[11] Taylor M. & Murphy S. (1997). A decade of Technigalva. *Proceedings of 18th International Galvanizing Conference*. Birmingham: EGGA.

[12] Schubert P. & Schulz W.-D. (2001). *Der Einfluss von Zinkbadzusatzen.* Forschungsbericht FB410/01/01 des Instituts fur Korrosionsschutz. Dresden.

[13] Dreulle N., Dreulle P. & Vacher J.C. (1980). *Das Problem der Feuerverzinkung von siliziumhaltigen Stahlen*. Metallwissenschaft und Technik, 34(9), 834–838.

[14] PN-EN ISO 1461:2011 – Powłoki cynkowe nanoszone na wyroby stalowe i żeliwne metodą zanurzeniową. Wymagania i metody badań.

[15] PN-EN ISO 6507-1:2007 Metale. Pomiar twardości sposobem Vickersa. Część 1. Metoda badań.

[16] Marder A. (2000). The metallurgy of zinc-coated steel. *Progress in Material Science*, 45(3), 191–271.