16. Zinc and Zinc Alloys

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This chapter presents key facts about zinc's role in the world together with technical reasons for its widespread use. The frequency and occurrence of zinc resources are compared with present and forecast demand, showing that more than 200 years of future demand will be met by known zinc resources. An overview of the primary zinc production process is then given, including an overview of the mining, aqueous concentration, roasting, cementation and electrolytic refining steps. Mechanical, thermal and crystallographic properties of zinc are then provided, especially for the most widely produced and used grade, 99.99% (special high grade) zinc. The principal uses of zinc and its alloys are then described. The most important use of zinc is the corrosion protection of steel; the usual reactions occurring during corrosion of galvanized steel are given together with corrosion rates typical of many environments where it is used. The next most important use is zinc die casting alloys; the composition of these alloys and their engineering properties are provided. Compositions and technical characteristics of other applications including rolled and thermal sprayed zinc, as well as zinc anodes, are also given.

Zinc is an abundant component of the Earth's crust. It is estimated that the amount of zinc in the first mile of the Earth's crust, under dry land, is 224 trillion (2.24×10^{14}) metric tons. Under the oceans and in the seabed, the amount of zinc is 15 billion (1.5×10^{10}) metric tons. Zinc ore deposits are widely spread throughout the world, with zinc ores being extracted in more than 15 countries. Zinc is normally associated with lead, gold, silver and copper in deposits. Available zinc resources, which include the identified concentration of zinc in the Earth's crust in a form for which economic extraction is currently or potentially feasible, total 1.9 billion tons. Of this, 480 million tons are, or may become in the close future, available for production. Of the world's zinc reserves known in 2010, 21% were in Australia, 17% in China, 9% in Peru, 7% in Kazakhstan, 6% in Mexico, 5% in the USA, with the remaining balance in other countries. Together with primary sources of zinc, recycling of zinc products is increasing in volume. It is currently estimated that about 66% of all zinc used in Europe is recycled [16.1]. In 2017, zinc metal demand was 14.1 million tons, meaning that given available reserves of 250 million tons, 18 years of demand are available from currently developed reserves. However, reserve bases and available economically developable resources will supply over 140 years of current demand, if no recycling sources are available. Given the increasing volume from recycled sources, it is expected that available zinc resources can serve demand for at least 200 years, based on known deposits.

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16.1 Naturally Occurring Zinc

There are four types of zinc-bearing geologic materials, each of which contributes about equally to the supply of zinc for metallurgical smelting:

1. Carbonate-hosted deposits, including limestones and dolomites
2. Shales of the black marine type, or siltstones or their metamorphic equivalents – sillimanite, schists and gneisses
3. Volcanogenic and massive sulfide bodies
4. Skarn and manto types of ore body, mostly of tertiary origin.

Most mining operations are conducted underground, although there are several large open-pit mines. Concentration of ores is carried out by flotation, followed by grinding. Roasting to zinc oxide is then typically the next step, followed by leaching in sulfuric acid to prepare a solution for electrolytic zinc production. Iron is then precipitated as jarosite, goethite or hematite. These iron- and zinc-bearing residues can be further treated to recover between 10% and 15% of the extra zinc previously lost. All elements to be removed from the zinc feed lie below zinc in the electrochemical series and can be precipitated by cementation. This is done by adding zinc dust to the solution. In the electrolytic refining process, a solution of zinc sulfate is electrolyzed between anodes typically made of lead alloys and aluminum cathodes. Zinc is deposited on the cathodes and periodically removed. The cathodes are stripped and then sent to a casting house where alloying and ingot casting are conducted. A small fraction of world zinc production continues to be produced by thermal reduction, including blast furnace reduction of sintered zinc-rich feeds. Thermal reduction accounted for 90% of zinc production in the early 1900s but is now less than 15% of world production [16.2].

16.2 Zinc Metal Grades And Standards

Compositions of pure zinc are shown in Table 16.1. These show the several grades according to ISO 752 *Zinc Ingots* and ASTM 6 *Standard Specification for Zinc* that are the most widely used standards for pure zinc. The most widely produced and used grade is the 99.99% (special high grade) zinc.

Table 16.1 Composition of unalloyed zinc (ingots or slabs)

Standard	Zn min (%)	Pb max (%)	Cd max (%)	Sn max (%)	Fe max (%)	Total Pb + Cd + Sn + Fe + Cu max (%)
ISO 752						
Zn99.995	99.995	0.003	0.003	0.001	0.002	0.0050
Zn99.99	99.99	0.003	0.003	0.001	0.003	0.010
Zn99.95	99.95	0.03	0.02	0.001	0.02	0.050
Zn98.5	98.5	1.4	0.20	–	0.05	1.50
Zn98	98	1.8	–	–	0.08	2.0
ANSI/ASTM B6						
LME grade	99.995	0.003	0.003	0.001	0.002	0.01
Special high grade	99.990	0.003	0.003	0.001	0.003	0.01
High grade	99.90	0.03	0.02	–	0.02	0.063
Intermediate grade	99.5	0.45	0.01	–	0.05	0.71
Prime western	98.0	1.4	0.20	–	0.05	1.85

16.3 Properties of Zinc

The mechanical properties of pure zinc are shown in Table 16.2. The tensile strength and elongation figures are not usually of practical interest, but the information shown indicates the sensitivity of these properties to zinc purity.

The thermal properties of zinc are shown in Table 16.3. Zinc is not combustible and does not spark when struck by steel tools, which makes it valuable for use in environments where explosives and combustibles are present. The boiling point of zinc is among the

Table 16.2 Mechanical and physical properties of pure zinc

Tensile strength (cast)	28 MN m^{-2} (4000 psi)
(rolled – with grain)	
99.95% zinc soft temper	126 MN m^{-2} (18 000 psi)
98.0% zinc hard temper	246 MN m^{-2} (35 000 psi)
Elongation (rolled – with grain)	
99.95% zinc soft temper	65%
98.0% zinc hard temper	5%
Modulus of elasticity	7×10^4 MN m^{-2} (1×10^7 psi)
Brinell hardness, 500 kg load for 30 s	30
Impact resistance (pressed zinc, elongation = 30%)	6.5–9 J cm^{-2} (26–35 ft lbs in^{-2})
Surface tension – liquid (450 °C)	0.755 N m^{-1}
Surface tension – liquid (419.5 °C)	0.782 N m^{-1}
Viscosity – liquid (419.5 °C)	0.00385 N m^{-1}
Velocity of sound (20 °C)	3.67 km s^{-1}
Coefficient of friction (rolled zinc versus rolled zinc)	0.21
Hardness	2.5 Mohs

Table 16.3 Thermal properties of pure zinc

Melting point	419.5 °C (692.7 K)
Boiling point (760 mm Hg)	907 °C (1180 K)
Combustion temperature	1800 °C (approximately)
Vapor pressure (419.5 °C)	1.39×10^{-1} mm Hg
Thermal conductivity	
Solid (18 °C)	113 W m^{-1} K^{-1}
Solid (410.5 °C)	96 W m^{-1} K^{-1}
Liquid (419 °C)	61 W m^{-1} K^{-1}
Liquid (750 °C)	57 W m^{-1} K^{-1}
Linear coefficient of thermal expansion:	
Single crystal along *a* axis 0–100 °C	15 µm m^{-1} K^{-1}
Single crystal along *c* axis 0–100 °C	61 µm m^{-1} K^{-1}
Polycrystalline 20–250 °C	39.7 µm m^{-1} K^{-1}
Volume coefficient of thermal expansion	
20–400 °C	0.89×10^{-6} K^{-1}
120–360 °C	0.85×10^{-6} K^{-1}
Contraction on freezing at 419.5 °C	4.48%
Volume change on freezing 469 °C → 0 °C	7.28%
Specific heat (20 °C)	0.382 kJ kg^{-1} K^{-1}
Latent heat of fusion (419.5 °C)	100.9 kJ kg^{-1}
Latent heat of vaporization (906 °C)	1.782 MJ kg^{-1}
Heat capacity	
Solid (298–692.7 K)	$C_\mathrm{p} = 22.40 + 10^{-3}\,T$ J mol^{-1} K^{-1}
Liquid	$C_\mathrm{p} = 31.40$ J mol^{-1} K^{-1}
Gas	$C_\mathrm{p} = 20.80$ J mol^{-1} K^{-1}

Table 16.4 Electrical, magnetic and electrochemical properties of pure zinc

Electrical resistivity:	
Polycrystalline at 20 °C	5.9 μΩ m
Liquid at 419.5 °C	37.4 μΩ m
Single crystal along *a* axis at 20 °C	5.83 μΩ m
Single crystal along *c* axis at 20 °C	6.16 μΩ m
Temperature coefficient of electrical resistivity:	
Between 0 and 100 °C	0.0419 nΩ m K^{-1}
Between −170 and 25 °C	0.0406 nΩ m K^{-1}
Pressure coefficient at 20 °C	
At 100–300 kPa	25 nΩ m TPa^{-1}
Superconductive at	0.84 ± 0.05 K
Magnetic susceptibility	
Polycrystalline at 20 °C	-0.123×10^{-6} mks
Single crystal along *c* axis at 20 °C	-0.169×10^{-6} mks
Single crystal along *a* axis at 20 °C	-0.124×10^{-6} mks
Electrochemical properties:	
Standard electrode potential	
• Against H_2 electrode	−0.762 V
• Hydrogen overvoltage	0.75 V at 108 A/m^2 for metal rubbed with fine emery
Temperature coefficient of overvoltage	−0.002 V/°C
Electrochemical equivalent	1.2195 kg/1000 A hr

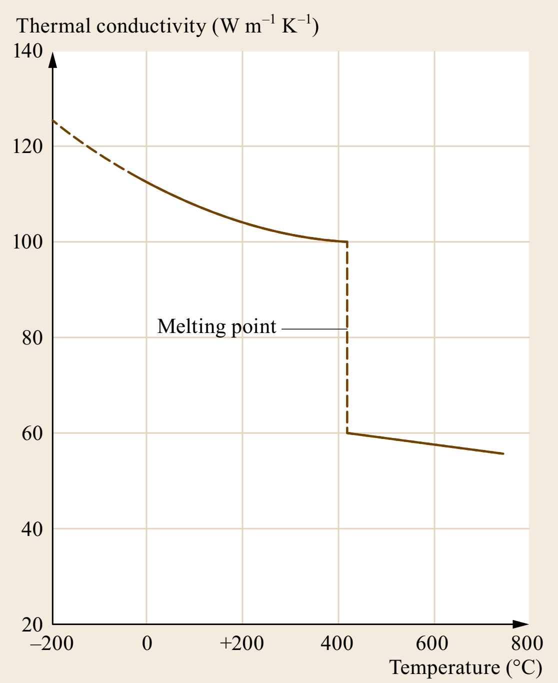

Fig. 16.1 Thermal conductivity of zinc (after [16.4])

lowest of the engineering metals. The US Bureau of Standards indicated that at 53 atmospheres the boiling point was raised to 1510 °C [16.3]. The vapor pressure of zinc is dependent upon temperature by the formula

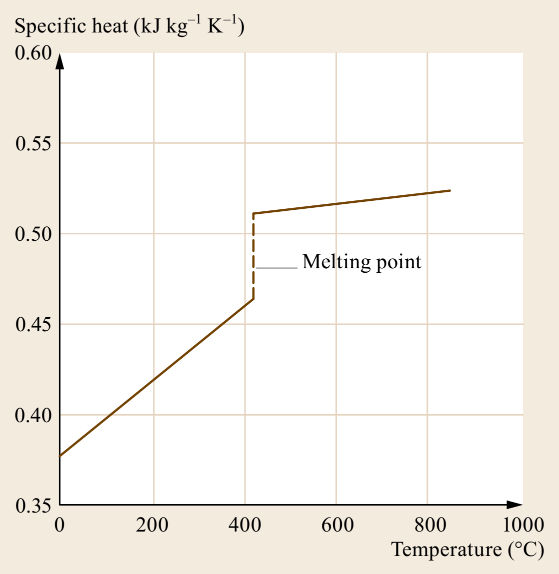

Fig. 16.2 Effect of temperature on the specific heat of zinc (after [16.4])

shown in (16.1)

$$\log_{10} P_{\mathrm{mm}} = 8.888 - \left(\frac{6888}{T}\right), \tag{16.1}$$

where P_{mm} = vapor pressure measured in millimeters of mercury and T = temperature in K.

Table 16.5 Atomic and crystallographic properties

Atomic number	30					
Atomic weight	65.37					
Metallic radius	1.38 Å					
Isotope abundance						
Mass number	64	66	67	68	70	
Terrestrial %	50.9	27.3	3.9	17.4	0.5	
Radioactive isotopes						
Mass number	62	63	65	69	72	73
Half life	9.5 h	38.3 m	250 d	57 m	2.1 d	< 2 m
Decay particles or process	K, β^+	β^+, K	K, β^+	β^-	β^-	β^-
Tetrahedral covalent radius	1.31 Å					
Ionic radius Zn^{2+}	0.74 Å					
Valency	2					
Valence electron configuration	$3d^{10}4s^2$					
Ionization potentials						
First	9.39 eV					
Second	17.87 eV					
Third	40.0 eV					
Chemical constant	1.136 atmospheres (theoretical)					
Density						
At 25 °C	7.14 mg m^{-3}					
Solid at 419.5 °C	6.83 mg m^{-3}					
Liquid at 419.5 °C	6.62 mg m^{-3}					
At 800 °C	6.25 mg m^{-3}					
Structure	Close packed hexagonal					
a	0.2665 nm at 25 °C (see text) or 0.2907 nm					
c	0.4947 nm at 25 °C					
c/a	1.856 at 25 °C					
Twinning plane	$(10\bar{1}2)$ – pyramidal plane					
Slippage plane	(0001) – basal plane					
Cleavage plane	(0001) – basal plane					
Glide direction	$[11\bar{2}0]$					

The thermal conductivity of zinc decreases with increasing temperature, while the specific heat increases as shown in Figs. 16.1 and 16.2. Single crystals of zinc have a higher thermal conductivity than polycrystalline zinc. The thermal conductivity also varies with crystallographic direction. Electrical, magnetic and electrochemical properties are shown in Table 16.4. Electrical resistivity measurements were made at 99.993% zinc [16.5]. The effect of pressure and temperature on electrical resistivity is shown in Figs. 16.3 and 16.4. Zinc is diamagnetic, therefore it has a magnetic permeability less than 1. Zinc is anisotropic with regard to its diamagnetic susceptibility. Zinc shows a thermoelectric effect, meaning that when two ends of a zinc specimen are maintained at different temperatures, current will flow through an electrical circuit joining these ends. Values for a polycrystalline spectrographically pure zinc against platinum when the cold junction is maintained at 0 °C show a voltage of 0.758 mV when the hot junction is 100 °C; 1.894 mV at 200 °C and 5.29 mV at 400 °C. The atomic and crystallographic properties of zinc are shown in Table 16.5. The normal valence states are Zn (I) and Zn (II). Compounds of zinc (I) do not exist in nature, although ZnH, ZnBr, and ZnCl are known as spectrographic species. Zinc is generally divalent and can donate two outer electrons to form an electrovalent compound; for example, zinc carbonate ($ZnCO_3$). It may also share those electrons, such as in $ZnCl_2$, in which the bonds are partly ionic and partly covalent. Zinc crystallizes in the hexagonal system, but while the crystal structure is considered to be of a close packed hexagonal type, the c/a axial ratio is 1.856, much greater than the theoretical 1.633 calculated for this system. As required by the hexagonal close packed system, each zinc atom has 12 nearest neighbors, but six are one distance apart at 0.2665 nm, and six are further apart at 0.2907 nm. It has been reported that the bonds in the hexagonal basal plane are appreciably stronger than those between planes [16.6]. This explains much of the behavior of the metal under

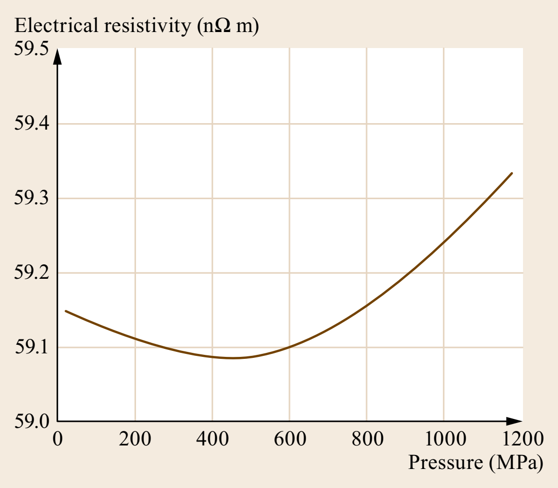

Fig. 16.3 Effect of pressure on electrical resistivity (after [16.4])

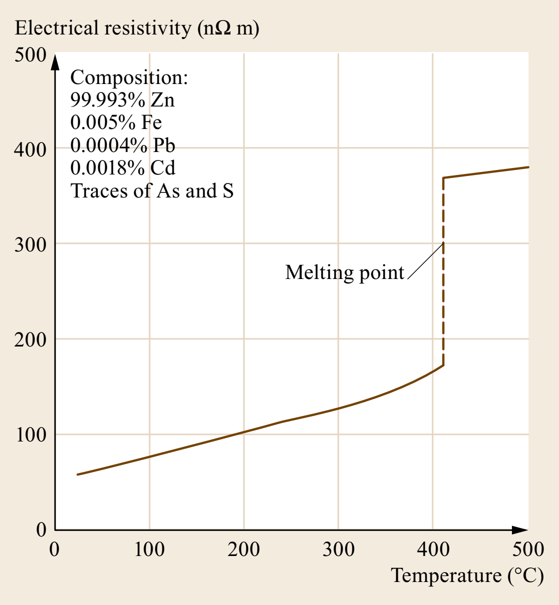

Fig. 16.4 Effect of temperature on electrical resistivity (after [16.4])

deformation and the anisotropy of the zinc crystal. With a c/a ratio greater than 1.633, only basal slip will occur. At ratios less than 1.633, slip will occur on other planes as well. Because bonding between basal planes is relatively weak, when accommodating stress the lattice first tends to slip along such planes. In such slip there is movement of part of the lattice along the basal planes so that the basic crystal structure is maintained. Above room temperature, slip may also occur along the prismatic (1010) plane.

16.4 Uses of Zinc

The largest use of zinc is as a protective coating for steel, where it provides both barrier and sacrificial protection. Zinc coating can be applied to steel articles after they are fabricated, in which case a mainly pure zinc coating is used. For the coating of steel sheet, wire and other products in a continuous process, different zinc alloys are used. The different zinc compositions used for sheet steel coatings are shown in Table 16.6. In many atmospheric, aqueous and other environments, zinc coatings are able to form a protective scale layer consisting of a mixture of zinc oxide, zinc hydroxide and various basic salts, depending upon the environment, providing useful corrosion lives. The formation of the protective layers is mainly influenced by the pH of the environment. Zinc forms an amphoteric oxide, and therefore both acid and alkaline conditions can interfere with the formation of protective layers. Figure 16.5 shows how the corrosion rate of zinc varies with pH. Attack is seen to be most severe at pH levels below 6 and above 12.5, whereas within this range the corrosion rate is slow. In general, zinc corrodes by a slow general dissolution process. Pitting corrosion only occurs under special considerations; for example, in water where a scale may crack, locally exposing a small anodic area. Intergranular corrosion of cast zinc was historically a problem until it was found that this was due to certain impurities, especially lead, tin and cadmium. The use of high-purity zinc prevents the occurrence of intergranular corrosion caused by these elements. The surface corrosion rates of zinc are not greatly affected by the purity of zinc: 98.0% zinc and 99.99% zinc behave similarly in many conditions. The aluminum-containing coatings for continuous galvanizing products greatly improve corrosion resistance and are widely used in industry. Zinc-iron (galvannealed) coatings are also widely used, especially in automotive applications. In addition, zinc-iron coatings can be more than 30% more resistant to corrosion than pure zinc in mildly acidic conditions. The main reactions of zinc coatings during the corrosion process are shown in Table 16.7. Examples of atmospheric corrosion rates of zinc-coated steels at typical outdoor sites are shown in Table 16.8.

Zinc is also widely used in casting alloys, mainly for pressure die casting. The main zinc casting alloys are composed of zinc, aluminum and magnesium, with additions of copper to improve strength in several in-

Table 16.6 Representative zinc alloy compositions used for coating of sheet steel

Name	Al (wt%)	Mg (wt%)	Other (wt%)
Normal Galvanize (GI)	0.14–0.3	0	
Galvanneal (GA)	0.11–0.135	0	10–14 Fe
Galfan®	5	0	0.03–0.10 Ce + La
Galvalume®	55	0	1.5 Si
MagiZinc®	1.5	1.5	
Magnelis®	3.5	3	
ZAM®	6	3	
Super Dyma®	11	3	

Galfan is a trademark of Galfan Technology Centre Inc.
Galvalume is a trademark of BIEC International Inc.
MagiZinc is a trademark of Tata Steel Europe
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stances. Table 16.9 shows the compositions of standard zinc casting alloys. Zinc die casting alloys possess an attractive combination of properties, including low melting point, high precision, the ability to be finished with a wide variety of surface treatments and long tool life. The physical and mechanical properties of the major zinc casting alloys are shown in Tables 16.10 and 16.11.

Rolled zinc alloys can be produced as sheet, strip, plate, rod and wire. Because of the hexagonal closed-packed crystallography of zinc, modification is needed in the rolling techniques commonly employed for other metals. Unalloyed zinc also recrystallizes at room temperature so that the effects of work hardening are quickly removed. Therefore, it is not possible to harden zinc appreciably by mechanical working. Rolled zinc alloys used in buildings have compositions shown in Table 16.12. Their physical and mechanical properties are shown in Tables 16.13 and 16.14. Rolled zinc may be formed by many techniques, including bending, spinning, stamping, deep drawing, rollforming, coining and impact extrusion. A special class of proprietary alloys is used in deep-drawn conditions for production of dry cell battery calots.

Zinc wire is also used to produce thermal sprayed coatings for the protection of steel. Thermal spray alloys include pure zinc and also a zinc-15% Al alloy that shows superior performance in marine and other salt-laden environments. This sprayed coating is produced by melting zinc powder or wire in a flame or electric arc and projecting molten droplets by air or gas onto a grit-blasted steel surface that is to be coated. The corrosion resistance of the pure zinc coating is similar to that of galvanized coatings discussed earlier.

Zinc anodes are used when it is possible to connect a steel structure to zinc by an electrical connection through the conductive medium of the environment. This includes the anodic protection of immersed structures such as ships and pipelines. The compositions

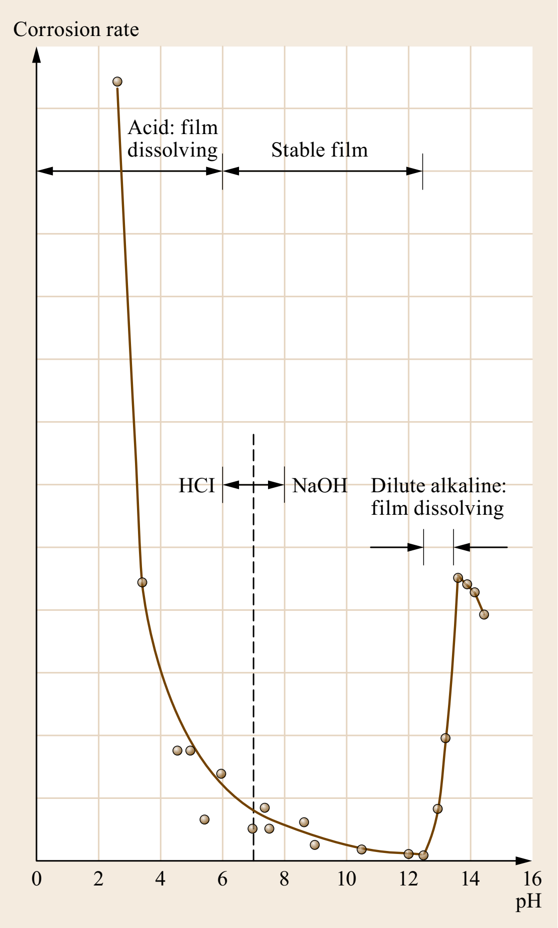

Fig. 16.5 Variation of corrosion rate with pH (after [16.7])

of zinc anodes used to protect steel in sea water are shown in Table 16.15. The rate at which zinc anodes are consumed in sea water is about 12 kg yr^{-1}. On bare steel the current density is about 0.1 A m^{-2}, so to protect 100 m^2 of bare steel requires about 120 kg yr^{-1} of zinc anodes. In other environments, the life of the anode depends upon the severity and the conductivity of the medium. In certain soils, for example, zinc anodes used together with protective coatings have lives up to five years. After this time, the zinc anode can be replaced and a further period of protection obtained. Soils with a resistivity less than 5 Ω cm are sufficient to provide galvanic protection by the zinc for the steel.

Table 16.7 Zinc corrosion reactions in different atmospheres (schematic). CO_2 has been included as an attacking substance because it participates in the formation of corrosion products. However, CO_2 is also necessary to form stable films (after [16.8])

Type of atmosphere	Attacking substances	Corrosion products		
		Composition	Relative solubility in water	Corrosion rate
Rural	$O_2 + H_2O + CO_2$	$ZnO \rightarrow Zn(OH)_2 \rightarrow 2ZnCO_3 \cdot 3Zn(OH)_2$	Very low	Very low
Marine	$O_2 + H_2O + CO_2 + Cl$	$ZnO \rightarrow Zn(OH)_2 \rightarrow$ $2ZnCO_3 \cdot 3Zn(OH)_2 \rightarrow$ $\left\{\begin{matrix} ZnCl_2 \cdot 4Zn(OH)_2 \\ ZnCl_2 \cdot 6Zn(OH)_2 \end{matrix}\right. + \left\{\begin{matrix} Zn_3OCl_4 \\ Zn_4OCl_6 \end{matrix}\right.$	Moderate	Low
Urban and industrial	$O_2 + H_2O + CO_2 + SO_2$	$ZnO \rightarrow Zn(OH)_2 \rightarrow 2ZnCO_3 \cdot$ $3Zn(OH)_2 \rightarrow ZnS + ZnSO_3 + ZnSO_4$	Good	High

Table 16.8 Zinc one-year corrosion rates, ratio of steel corrosion to zinc corrosion, and site atmospheric characteristics (after [16.9])

Test site	Zinc corrosion 1-yr results (μm)[a]		Steel/zinc ratio, mean, 1-yr results (μm)		Environmental characteristics[b]		
	Flat	Helix of wire	Flat	Helix	Cl, mean (mg m^{-2})	SO_2 (mg m^{-2})	Time of wetness (TOW), mean (h, per annum)
Iguasu	1.6		4		Semiarid, wet, rural		5680
Camet	1.3		28		Subtropical, marine, wet		6088
Buenos Aires	1.0		16		Subtropical, marine, wet		4645
San Juan	0.2		23		Subtropical, dry, rural		855
Yubany Base	1.9		19		Antarctic, desert		2693
Boucherville	1.4	2.0	17	14	59	16	1396
Kasp Hory	1.9	2.2	14	22	Rural	17	3206
Praha-Bachov	2.8	3.3	17	21	Urban	67	2991
Kopisty	3.5	4.8	20	23	Industrial	90	2444
Helsinki	1.3	2.6	26	16	4	19	3578
Otaniemi	0.9	1.8	28	21	3	15	3256
Athari	0.7	1.2	18	13	Rural	4	3105
St. Denis, Paris	1.5	3.6	25	14	28	50	4268
Ponteau Mart	2.6	13.4	28	9	241	87	3846
Richerande	0.9	2.2	18	10	7	9	4171
St. Remy	1.5	4.2	29	23	378	30	6310
Salin de Gir	4.6	5.7	16	23	184	20	3311
Ostende (Belgium)	5.1	10.6	19	12	173	24	6083
Paris	3.0	2.8	14	18	Urban	53	3189
Auby	5.6	8.5	19	17	16	188	4571
Biarritz	4.3	8.2	20	8	193		
Bergisch Glad.	1.6	1.8	23	29	Urban	18	4267
Choshi	1.4	2.8	31	33	56	8	5704
Tokyo	1.5	1.5	26	26	4	15	2173
Okinawa	3.4	8.8	22	12	97	11	3852
Judgeford, Wellington	0.7	1.2	29	30	Rural-marine		
Oslo	1.3	1.8	19	19	2	14	2641
Borregaard	3.8	5.7	16	16	9	44	3339

Table 16.8 (continued)

Test site	Zinc corrosion 1-yr results (μm)[a]		Steel/zinc ratio, mean, 1-yr results (μm)		Environmental characteristics[b]		
	Flat	Helix of wire	Flat	Helix	Cl, mean (mg m^{-2})	SO$_2$ (mg m^{-2})	Time of wetness (TOW), mean (h, per annum)
Birkenes	2.3	2.0	9	14	Acid rain	1	4138
Tananger	3.0	3.3	20	22	308	4	4583
Bergen	2.1	2.2	13	15	7	9	4439
Svanvik	0.8	1.4	25	21	1	17	2605
Murmansk	1.1	2.1	28	25	19	5	3227
Batum	1.6	2.0	18	14	1	26	3216
Vladivostok	2.3	3.1	11	22	18	29	3920
Oymyakon	0.4	0.6	2	3	Cold	5	381
Madrid	0.6	1.6	46	18	Urban	44	2060
El Prado	0.5	1.2	31	18	Urban	5	3223
Lagoas-Vigo	1.0	2.5	27	14	29	49	2840
Baracaldo-Vizcaya	1.2	2.6	37	22	25	32	4375
Stockholm Vana	0.6	1.5	41	28	Urban	10	
Kattesand	1.5	2.8	23	22	76	5	
Kyamyk	1.8	3.5	34	19	650	5	
Stratford	1.7	1.5	23	34	Industry	20	5783
Crowthorne	1.1	1.2	34	48	Rural		
Rye	2.5	2.0	23	46	Marine	21	
Fleet Hall	1.3	2.3	29	25	Urban		
Kure Beach	2.0	3.9	19	21	102	10	4289
Newark	2.0	2.2	13	12	Industrial		
Panama CZ	17.5	7.6	21	39	619[c]	52	7598
Research Triangle	0.8		28		Urban		
Point Reyes	1.7	3.5	23	42	Marine		
Los Angeles	1.1	1.8	20	11	Urban, marine	20	4003

[a] The zinc corrosion results are normally the mean of 18 determinations (three replicates for six one-year exposures starting in spring and autumn for three years).

[b] Where no atmospheric data are available, a quantitative description of the site is given.

[c] Marine splash zone.

Table 16.9 Typical composition of zinc–aluminum pressure die-casting alloys

Element (wt%)	Alloy 2	3	5	7	ZA-8
Aluminum	3.5–4.3	3.5–4.3	3.5–4.3	3.5–4.3	8.2–8.8
Copper	2.5–3.5	0.25 max	0.5-1.25	0.25 max	0.8–1.3
Magnesium	0.02–0.06	0.01–0.06	0.03–0.08	0.005	0.02–0.03
Iron (max)	0.10	0.10	0.10	0.075	0.065
Lead (max)	0.005	0.005	0.005	0.0030	0.005
Cadmium (max)	0.004	0.004	0.004	0.0020	0.005
Tin (max)	0.003	0.003	0.003	0.0010	0.002
Tellurium + indium (max)	0.0015	0.0015	0.0015	0.0010	–
Nickel	–	–	–	0.005–0.020	–

Alloy 2 is best known as the German DIN 1743 Alloy Z430 and ASTM AC43A.
Alloy 3 is also ISO 301 Alloy ZnA14, BSI Alloy A, ASTM AG40A, UNS Z33521, German Alloy Z 400.
Alloy 5 is also ISO 301 Alloy ZnA14Cu1, BSI Ally B, ASTM AC41A, UNS Z33530, German Alloy Z 410.
Alloy 7 is best known as ASTM AC40B.

Table 16.10 Physical properties of the zinc-aluminum pressure die casting alloys (after [16.10])

Physical Property	Alloy				
	2	3	5	7	ZA-8
Specific gravity (kg m^{-3})	6.6	6.6	6.7	6.6	6.3
Solidification temperature range (°C)	390–379	387–381	386–380	387–381	375–404
Solidification shrinkage (%)	1.25	1.17	1.17	1.17	1.1
Thermal expansion coefficient at 20−100 °C ($\times 10^{-6}$ K^{-1})	27.8	27.4	27.4	27.4	23.3
Electrical conductivity (% IACS)	25	27	26	27	27.7
Electrical resistivity at 20 °C (μΩ cm)		6.37	6.54		6.2
Thermal conductivity at 70−140 °C (W m^{-1} K^{-1})	105	113	109	113	114.7
Heat capacity at 20−100 °C (J kg^{-1} h^{-1})	418.7	418.7	418.7	418.7	435.4

Table 16.11 Typical mechanical properties at 20−21 °C of alloys 2, 3, 5, 7 and 8 (after [16.10])

Property	Alloy									
	2		3		5		7		8	
	As Cast	Aged	As Cast	Aged	As Cast	Aged	As Cast	Aged	As Cast	Aged
Ultimate tensile strength (MPa)	358	283	328	283	374	331	241	269	241	297
Yield strength (0.2% offset) (MPa)		220	230		290					225
Elongation (on 51 mm) (%)	8	10	7	12	8	2	16	13	18	20
Hardness (Brinell – 500 kg)	100	82	91	80	103	98	72	80	67	91
Shear strength (MPa)	317	214	262	214	275					227
Compressive yield strength (0.1% offset) (MPa)	641	414	600	414	252					171
Impact energy (unnotched bar 6.35 × 6.35 mm^2) (J)	47	58	65	58	42	6.8	55.6	54.2	55.6	17

Table 16.12 Typical chemical compositions of rolled zinc alloys (percent by weight) (after [16.10])

Alloy Family	Alloying elements							Impurities			
	Cu	Ti	Al	Mg	Cd	Pb	Fe	Pb	Fe	Cd	Cu
Pure zinc								< 0.003	< 0.002	< 0.003	< 0.001
					0.004–0.006			< 0.01	< 0.002		
Zn-Cu	0.7–0.9		0.002		0.005		0.008	< 0.02	< 0.008	< 0.02	
Zn-Cu-Ti	0.7–0.9	0.08–0.14	0.005		0.02	0.02	0.01	< 0.020	< 0.010	< 0.020	
	0.4–0.5	0.15	0.002					< 0.003	< 0.002	< 0.003	
	0.18	0.08	0.002					< 0.003	< 0.002	< 0.003	
Zn-Pb-Cd-Fe	0.002				0.04–0.06	0.06–0.08	0.008		< 0.008		< 0.002
					0.015	0.2–0.3	0.005				< 0.001
					0.005	0.6–0.7			< 0.002		< 0.001
Zn-Al (superplastic alloy)	0.4–0.6		21–23	0.008–0.012				< 0.01		< 0.01	

Table 16.13 Physical properties of rolled zinc (after [16.10])

Property	Alloy family				
	Pure zinc	Zn-Cu	Zn-Cu-Ti	Zn-Pb-Cd-Fe	Zn-22% Al
Density (g/cm^3)	7.14	7.17	7.17–7.2	7.14	5.2
Melting point (°C)	419	422	420	419	
Specific heat capacity (J kg^{-1} K^{-1})	393.5	401.9	401.9	393.5	
Thermal expansion, with grain (µm mm^{-1} K^{-1})	30	34.7	20.0–24.0	32.6	22.1
Thermal expansion, against grain (µm mm^{-1} K^{-1})	20	21.1	16.0–19.4	23	22.1
Thermal conductivity (W m^{-1} K^{-1})	104.7	104.7	104.7	107.6	
Electrical conductivity (%IACS)		28	27	32	
Electrical resistivity (µΩ cm)			6.24	6.06	6

[a] Typical values

Table 16.14 Mechanical properties of rolled zinc alloys (after [16.10])

Property	Alloy family				
	Pure Zinc	Zn-Cu	Zn-Cu-Ti	Zn-Pb-Cd-Fe	Zn-22% Al[a]
Tensile strength (MPa)					
With grain	120^{d}		$160–193^{d}$	$110–140^{d}$	379.2^{b}
		$172–207^{c}$	$165–207^{e}$	$124–165^{e}$	
Against grain	150^{d}		$200–280^{d}$	$140–180^{d}$	441.2^{c}
		$214–262^{e}$	$207–262^{e}$	$152–193^{e}$	
Elongation (%)					
With grain	$60–90^{d}$		$35–70^{d}$	$80-90^{d}$	25^{b}
		$25–45^{e}$	$25–45^{e}$	$30–65^{e}$	
Against grain	$40–60^{d}$		$15–80^{d}$	$40–80^{d}$	9^{c}
		$20–36^{e}$	$20–36^{e}$	$24–52^{e}$	
Yield strength (MPa) (0.2%)					
With grain			125^{d}		296.5^{b}
Against grain			177^{d}		386.1^{c}
Young's modulus (MPa)					
With grain			$63\,500^{d}$		$93\,000^{b}$
Against grain			$88\,000^{d}$		$68\,250^{c}$
Vickers hardness	30^{d}		$51–75^{d}$	30	
Rockwell hardness		$55–65^{e}$	$54–66^{e}$	$41–58^{e}$	79^{b} 85^{c}
Creep rate at 25 °C and a stress of 68.95 MPa (% hr^{-1})			0.00001–0.0004		
Stress to produce 1% creep in 11.4 yr (0.01% in 1000 hr) (MPa)					24.8^{b} $55–69^{c}$
Shear strength (MPa)		138–152	138–152	124–138	

[a] Superplastic alloy.
[b] As rolled.
[c] Annealed at 350 °C.
[d] Based on [16.11].
[e] Based on thermomechanical treatment applied.

Table 16.15 Zinc anode specifications for use in sea water

Specification	MIL-A-18001H 1968 (%)	ASTM B418-12 2012	
		Type 1 (%)	Type 2 (%)
Aluminum	0.10–0.50	0.10–0.4	0.005 max.
Cadmium	0.025–0.15	0.03–0.10	0.003 max.
Iron, max.	0.005	0.005	0.0014
Lead, max.	0.006		
Copper, max.	0.005		
Silicon, max.	0.125		
Zinc	Remainder	Remainder	Remainder

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