

EFFECT OF HEAT TREATMENT ON THE INTERLAYER AND CORROSION
BEHAVIOR OF Zn AND Zn-0.5%Al COATED HIGH CARBON STEEL FOR
MARINE APPLICATION

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*Specially dedicated to
my beloved family and supervisor
for their support and inspiration*

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ABSTRACT

Hot dip galvanizing has been an important technique for corrosion protection in the industry. In recent years, longer service life for hot dip galvanized steel is thus crucial to offset the rapid rises in cost of maintenance in service. This project is aimed to investigate the effects of heat treatment on the intermetallic and corrosion behaviour of Zn and Zn-0.5%Al coated high carbon steel wire rope for marine application. A total of nine set of heat treatment parameters with heating time one, three and five hours at temperatures 250, 350, 400°C respectively were conducted onto Zn and Zn-0.5%Al coated high carbon steel substrate (0.87%C). These parameters were to evaluate the effects of heat treatment time and temperature on the microstructural evolution and formation kinetics of the coating. The coated steels had undergone corrosion tests namely salt spray test and electrochemical test. The samples before and after corrosion test were analyzed with optical microscopy, scanning electron microscopy, energy dispersive X-ray and X-ray diffractometer. The result shows that heat treatment affects the coating thickness and weight loss due to powdering effect. Besides, by increasing heat treatment time and temperature, it was observed that the gamma layer for Zn-coated steel was increased. However, the growth rate of gamma layer for Zn-0.5%Al galvanized wire rope was slow. It was also observed that heat treatment affects the corrosion rate of Zn and Zn-0.5%Al coated samples. The optimum heat treatment parameter for Zn coated samples was heating at temperature 350°C for 3 hours which gives the lowest corrosion rate. Optimum heat treatment parameter for Zn-0.5%Al coated samples was heating at temperature 400°C for 5 hours.

ABSTRAK

Celup panas penggalvanian merupakan satu teknik yang penting untuk perlindungan kakisan dalam industri. Sejak kebelakangan tahun ini, jangka masa perkhidmatan yang panjang daripada keluli bergalvani adalah penting untuk mengimbangi peningkatan pesat dari segi kos penyelenggaraan. Projek ini bertujuan untuk menyiasat kesan-kesan rawatan haba pada kelakuan antara logam dan prestasi kakisan salutan Zn dan Zn-0.5% Al pada tali dawai keluli karbon tinggi untuk kegunaan marin. Sejumlah sembilan set parameter rawatan haba dengan masa pemanasan satu, tiga dan lima jam pada suhu 250, 350, 400°C masing-masing telah dijalankan ke atas salutan Zn dan Zn-0.5% Al pada substrat keluli karbon tinggi (0.87% C). Parameter ini adalah untuk menilai kesan masa dan suhu rawatan haba ke atas evolusi mikrostruktur dan kinetic pembentukan lapisan. Salutan keluli tersebut telah diuji dengan ujian kakisan iaitu ujian semburan garam dan ujian elektrokimia. Sampel sebelum dan selepas ujian kakisan dianalisis dengan mikroskop optik, pengimbasan elektron mikroskop, penyerakan tenaga sinar-X dan pembelau sinar-X. Hasilnya menunjukkan bahawa kesan rawatan haba mempengaruhi ketebalan lapisan dan kehilangan berat badan disebabkan oleh kesan powdering. Selain itu, dengan peningkatan masa rawatan haba dan suhu, ia telah diperhatikan bahawa ketebalan lapisan gamma untuk keluli salutan Zn meningkat. Walau bagaimanapun, kadar pertumbuhan lapisan gamma adalah lambat untuk salutan Zn-0.5% Al pada keluli tali dawai, Ia juga diperhatikan bahawa rawatan haba mempengaruhi kadar kakisan sampel salutan Zn dan Zn-0.5% Al. Parameter yang optimum untuk rawatan haba sampel salutan Zn ialah rawatan haba pada suhu 350°C untuk 3 jam yang memberikan kadar kakisan yang terendah. Rawatan haba yang optimum untuk sampel salutan Zn-Al 0.5% ialah rawatan haba pada suhu 400°C selama 5 jam.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C	Degree Celsius
K	Kelvin
μm	Micron
l	liter
M	Mega
Pa	Pascal
Å	Angstrom
H	Hydrogen
O	Oxygen
SO	Sulphur dioxide
Zn	Zinc
Fe	Ferrous
Al	Aluminum
NaCl	Sodium Chloride
CO ₂	Carbon dioxide
t	Time (min)
H ₂ O	Water

CHAPTER 1

INTRODUCTION

1.1 Introduction

Corrosion has been a major problem encountered by many industries and causes RM 500 million annually since 1981. Thus, many researches have been done in order to yield a better way to prevent and control against corrosion.

Hot dip galvanizing is one of the oldest and most important zinc (Zn) coating process. It has been applied for over 200 years and widely used in industry for corrosion protection of steels. The steel is protected by the Zn coating through a barrier effect and a galvanic effect, in which Zn acts as the sacrificial anode while steel acts as the cathode. In most atmospheric environments, Zn corrodes much less than steel, by a factor of 10 to 100 times (X. G. Zhang, 1996) due to the formation of a protective layer consisting of a mixture of Zn oxide, Zn hydroxide and various basic Zn salts depending on the nature of the environment. Thus the protection of steel by a Zn coating is mainly through the barrier effect. However, at the places where the Zn coating is damaged and the steel underneath is exposed, such as at cuts or at scratches, the galvanic action between steel and Zn can protect the exposed steel from corrosion.

In recent years, with the increasing requirements of industry for a longer service life for hot dip galvanized steel to offset the rapid rises in cost of maintenance

in service, a need for investigating the effect of heat treatment on the interlayer and corrosion behavior of Zn-Al coated High Carbon Steel for Marine application.

In this work, an investigation into the effect of heat treatment on the Zn, Zn-0.5%Al coating to observe the changes on intermetallic layer will be carried out.

1.3 Problem Statement

Galvanized wire ropes are exposed to seawater for a long period of time. Thus corrosion occurs and causes enormous losses. There are many methods to improve on the corrosion resistance of galvanized steel such as coating thickness, coating quality or perform heat treatment on the coating material. In this research, a study on the effect of heat treatment on the galvanized steel has been carried out in order to obtain better corrosion resistance of the coated layer.

1.4 Objectives of the Research

To investigate the effects of heat treatment of galvanized high carbon wire rope on the interlayer and corrosion behaviour of Zn and Zn-0.5%Al coated high carbon steel for marine application.

1.5 Scopes of the Study

The scopes of the study are based on the followings:

1. Selection of heat treatment parameters for coated high carbon steel wire ropes.
2. Perform heat treatment on the coated samples using high temperature furnace.
3. Microstructure evolutions were characterized by optical microscopy, X-Ray Diffraction, Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-Rays (EDX), elemental analysis.
4. The corrosion behavior were investigated by potentiodynamic polarization the on the coated and uncoated steel wire ropes.

REFERENCES

1. A.Chakraborty, R.K. Ray, D. Bhattacharjee, M. Dutta: Influence of substrate texture on the formation and growth of phase in the galvanized coatings on a few industrially produced Interstitial Free High Strength Steels; Galvatech 07; 2007; S. 499–503
2. A.T. Alpas, J. Inagaki: Effect of Microstructure on Fracture Mechanisms in Galvanized Coatings; ISIJ International, Vol. 40 2000, No. 2;2000; S. 172–181
3. Arcelor Mittal. Galvanized zinc-iron alloy coated steels, p 2. November, 2012
4. Badea, G. E., Caraban, A., Sebesan, M., Dzitacs, S., Cret, P., and Setel, A. Polarization measurements used for corrosion rates determination. Journal of sustainable energy. Vol. 1 No. 1, March, 2010.
5. Berduque, A., Dou, Z., and Xu, R.. Electrochemical studies for aluminum electrolytic capacitor applications: Corrosion analysis of aluminum in ethylene glycol-based electrolytes. Electronic Components Assoc., 2009; Inc. p 1-10.
6. C.E. Jordan, K.M. Goggins, A.R. Marder: Interfacial layer development in hot-dip galvanized coatings on interstitial free (IF) steel; Metallurgical and Materials Transaction A; 2007; S. 2101–2109.
7. C.S. Lin, M. Meshii, C.C. Cheng: Phase Evolution during Galvanized Process; Galvatech 95; 2005; S. 485–495
8. Chen, L., R. Fourmentin, J. R. McDermid. 2008. Met. Mat. Trans .A. 39A: 2008; 2128-2142
9. D. J. Paik, S.-G. Han, U.-Y. Son, J.-U. Lee, S.-Y. Choun, M.-H. Hong: Improvement of Galvanized Coating Properties through the Cooling Control of a fixed Soaking Furnace during Galvanizing Processes; Galvanizers Association Meeting Baltimore; 2008

10. Davis, J. R. (Ed.). Corrosion: understanding the basics. United States of America: ASM International; 2000.
11. Deits SH, Matlock DK. Formability of coated sheet steels: an analysis of surface damage mechanisms. In: Krauss G, Matlock DK, editors. Zinc-based steel coating systems: metallurgy and performance. Warrendale, PA: TMS, 2000. p. 297.
12. F.C. Porter, Corrosion resistance of zinc and zinc alloys, M. Dekker, New York, 2004.
13. F.C. Porter, Zinc handbook: properties, processing, and use in design, Marcel Dekker, New York, 2001.47.
14. Gallo E, Matlock DK. The importance of microstructure on the formability of galvanized I.F.sheet steel. GALVATECH '95. Chicago, IL: Iron and Steel Society, 2005. p. 739
15. Goggins KM, Marder AR. Crack initiation and propagation in hot-dip galvanized steel sheet during bending. 3rd International Conference on Zinc Coated Sheet, Barcelona 2001;S4I:1-11.
16. Gong, Y.F., T. J. Song, H. S. Kim, J. H. Kwak, B. C. De Cooman. Proceedings of the Asia-Pacific Galvanizing Conference, The Corrosion Science Society of Korea, Jeju, Korea, November 2012, paper B-15.
17. Guth J, Maigne JM. Comparing spot-weldability of galvanized coated steel sheets: mechanism and base metal influence. GALVATECH '95. Chicago, IL: Iron and Steel Society, 2005. p. 709.
18. Guttmann M, Lepretre Y, Aubry A, Roche M-J, Moreau T, Drillet P, Maigne JM, Baudin H. Mechanism of the galvanizing reaction. Influence of Ti and P contents in steel and of its surface microstructure after annealing. In: GALVATECH '95. Chicago, IL: Iron and Steel Society, 2005.
19. H. B. Chen, K.-M. Hsu: Improvement of the Powdering Resistance of 340H Bake-Hardening GA Sheet Steel; Galvatech 04; 2004; S. 559–564
20. H. E. Townsend, in ASM Metals Handbook, American Society for Metals, Materials Park, Ohio, 2004.

21. Hamed Asgari Moslehabadi, Galvannealing of Dual Phase Steels.MSc (Isfahan University of Technology) 2012
22. Hisamatsu Y. Science and technology of zinc and zinc alloy coated sheet steel. GALVATECH'89. Tokyo: The Iron and Steel Institute of Japan. 1999. p. 3.
23. J. C. Zoccola, H. E. Townsend, A. R. Borzillo, and J. B. Horton, in Atmospheric factors affecting the corrosion of engineering metals, STP 646, p. 165-184, American Society for Testing and Materials, Philadelphia, 1978.
24. J. H. Selverian, A. R. Marder, and M. R. Notis, Met. Trans., 20A, 543 2009
25. J. Kawafuku, J. Katoh, M. Toyama, H. Nishimoto, k. Ikeda, and H. Satoh, J. IronSteel Inst. Jpn., 77, 995-1002 2001.
26. J. L. Murray, Binary alloy phase diagrams, p. 185, T. B. Massalski Editor. ASM, Materials Park, OH, 2006.
27. J. Mackowiak and N. R. Short, Int. Met. Rev., No. 1, Review 237, 1999.
28. J. O. M. Bockris, Z. Nagy, and A. Danjanovic, J. Electrochem. Soc., 119, 285-295 2002.
29. J. P. Landriault, F.W. Harrison: CIM Bulletin, August 2007, pp. 71-78.
30. Jordan CE, Goggins KM, Marder AR. Interfacial layer development in hot-dip galvanneal coatings on interstitial free (IF) steel. Met Mater Trans 2004.
31. Kanamaru T, Nakayama M. Alloying reaction control in production of galvannealed steel. Mater Sci Res Int 2005;1:150.
32. Kim, M.S., J.H. Kwak, J.S. Kim, Y. H. Liu, N. Gao, N.Y. Tang. Proceedings of the Asia-Pacific Galvanizing Conference, The Corrosion Science Society of Korea, Jeju, Korea, November 8-12 2009.
33. KoÈ ster W, GoÈ decke T. Das DreistoÈ system Eisen-Aluminum-Zink. Z Metallkde 1970;61:642
34. Kubaschewski, Binary alloy phase diagrams, p. 1128, T. B. Massalski Editor. ASM, Metals Park, OH, 1996.p. 191-271.p. 295.
35. M. Sagiya, A. Hiraya, and T. Watanabe, J. Iron Steel Inst. Jpn., 77, 251-257 2001.
36. Marder AR. EÈ cts of surface treatments on materials performance. Materials selection and design. ASM Handbook, vol. 20. 2007. p. 470.

37. Marder, A.R., The metallurgy of zinc-coated steel. *Progress in Materials Science*, 2000
38. Maschek W, Hayes SP, Marder AR. Cross sectional studies of zinc iron phase growth in an environmental scanning electron microscope. In: GALVATECH '95. Chicago, IL: Iron and Steel Society, 2005 p. 309.
39. Odnevall and C. Leygraf, *Corros. Sci.*, 36, 1551-1567 2004.
40. Opbroek JB, Granzow WG. A deep drawing, hot-dipped galvanized steel for different forming applications, SAE Paper No. 850275. Warrendale, PA: SAE, 2005.
41. Osinski K. The influence of aluminum and silicon on the reaction between iron and zinc. Doctoral Thesis. Technical University, Eindhoven, 1983.
42. Pourbaix, Atlas of electrochemical equilibrium diagrams in aqueous solutions, p. 406-413, NACE, Houston, TX, 1974.
43. S. F. Radtke and D. C. Herrschaft, *J. Less Common Met.*, 93, 253 2003.
44. Smith, W. F. and Hashemi, J. *Foundations of Materials Science and Engineering*. (4th ed.). Mc Graw Hill International. 2006.
45. Tang N.Y. Thermodynamics and kinetics of alloy formation in galvanized coatings. In: Goodwin FE, editor. *Zinc-based steel coating systems: production and performance*. Warrendale, PA: TMS, 2008. p. 3
46. Urai M, Terada M, Yamaguchi M, Nomura S. *CAMP-ISIJ* 2008;1:651.
47. Urednicek M, Kirkaldy JS. Mechanism of iron attack inhibition arising from additions of aluminum to liquid Zn(Fe) during galvanizing. *Z Metallkde* 2007;64:649.
48. V. Ligier, M. Wery, J. Y. Hihn, J. Faucheu, and M. Tachez, *Corros. Sci.*, 41, 1139-1164 1999.
49. V. Rangarajan, N.M. Giallourakis, D.K. Matlock, G. Krauss: The Effect of Texture and Microstructure on Deformation of Zinc Coatings; *J. Materials Shaping Technology*; 1989; S. 217–227
50. V. Rangarajan, N.M. Giallourakis, D.K. Matlock, G. Krauss: The Effect of Texture and Microstructure on Deformation of Zinc Coatings; *J. Materials Shaping Technology*; 1989; S. 217–227

51. V. S. Muralidharan and K. S. Rajagopalan, *J. Electroanal. Chem.*, 94, 21-36; 2008.
52. Vander Heiden A, Burghardt AJC, van Koesveld W, van Perlstein EB, Spanjers MGJ. Galvanneal microstructure and anti-powdering process windows. In: Marder AR, editor. *The physical metallurgy of zinc coated steel*. Warrendale, PA: TMS, 2004. p. 251.
53. W. van Koesveld, M. Lamberigts, A. van der Heiden, L. Bordignon: Coating Microstructure assessment and control for advanced product properties of galvanized IF steels; *Galvatech 95*; 1995; S. 343–355
54. White CL, Lu F, Kimchi M, Dong P. Resistance welding electrode wear on galvanized steels. In: *Zinc-based steel coating systems: production and performance*. ed. Goodwin FE. Warrendale, PA: TMS, 2008. p. 219.
55. X. G. Zhang, *Corrosion and electrochemistry of zinc*, Plenum Press, New York, (2006).
56. Y. Suzuki, Y. Sugimoto, S. Fujita: Effect of internal oxidation of Galvanizing properties and anti-powdering properties of Si,Mn,P bearing high-tensile Galvanized Sheet steel; *Galvatech 07*; 2007; p.433–438
57. Yang, Y. Calcium and magnesium containing anticorrosion films on mild steel. Doctor Philosophy. Corrosion and Protection Centre, School of Materials. University of Manchester; 2010.