Advanced Materials Manufacturing & Characterization

Improving the Sink Roll life in Galvalume

Saurabh A. Bobde, S.D. Kshirsagar

Dept. of Mechanical Engineering, YCCE, Nagpur.

A R T I C L E   I N F O

A B S T R A C T

Galvalume is a Continuous Galvanizing Line. JSW Ispat Steel Ltd. Kalmeshwar has to frequently replace the sink roll assembly used in Zn-Al tank of the Galvalume. The mean time between replacements is very less as compared to expected mean time between failures (expected MTBF). This is due to deposition of zinc dross on the surface of roller. This result in uneven or improper Zn-Al coating on sheet surface. To avoid this sink roll has to replaced. The frequent replacement of roller assembly results in Stoppage of production, material loss, start-up loss and increased cost of production. This paper proposes an alternative material to extend the life of sink roll.

Introduction

Galvalume is a continuous hot dipping process in which steel sheet is dipped in Zn-Al pot. Zinc pot contains Aluminum (55%), Zinc (43.5%) and Silicon (1.5%). The hot dipping is carried out at 605^0 c. The chemical reaction between molten Zn-Al alloy with iron at 605^0c results in the formation of complex compound "dross". This dross deposits on sink roll surface. It causes:

1. Uneven deposition of dross on sink roll.
2. Impressions on sheet and variations in coating on sheet.
3. Sheet showing dross Build-up.

Due to this quality of sheet is lowered and sheet is downgraded. This downgrading brings financial loss to the company.
To avoid this, frequency of roller replacement is increased. However this has following disadvantages:

1. Increased loss of production due to frequent stoppages (During removal and refitting of assembly).
2. Zinc loss due to frequent change of roller assembly.
3. Additional cost of re-machining of sink roll.
4. Increase idle time in the process.

The project is aimed at increasing the life of sink roll or extending the time period between the sink roll replacements.

The increased time between replacements will help in overcoming the above disadvantages.

_____

Corresponding author: Saurabh A. Bobde
- E-mail address: ssaurabh_bobde@rediffmail.com
- Doi: http://dx.doi.org/10.11127/ijammc.2013.02.049

Sink Roll

TheSink roll, is a roll used in molten zinc tank in continuous galvanizing line. It is generally made of SS316L Ferrite free, stainless steel that can withstand extreme temperatures & high corrosion for extended periods of time. It made by centrifugal casting.[11] There body uses different shapes like straight body, crowned and tapered depending upon applications. A variety of groove patterns and pitches are made on the surface as per as customers specifications. Special grooves are provided for carbide coatings. [8]

Sink roll or Pot roll immersed in the molten zinc bath is affected by the dross is also attacked by the molten zinc leading to pitting and build ups. All these factors affect the coil surface. Such rolls have very short life. Sink rolls are works in a very corrosive environment, i.e. molten zinc. They typically see temperatures in excess of 600^0C for weeks at a time. Materials used are made to withstand this criteria, so they are also difficult to machine.[16] The roll is made of SS316L material. It is a ferrite free stainless steel grade having surface hardness RC 10. The body is a centrifugal cast stainless steel and the end ball/journal is from a static casting. Most of these rolls have no coatings on them. An uncoated roll may last up to 2 weeks, but with carbide coatings and special bushings they laste up to 5 weeks. However for Galvalume the life is reduced drastically due to dross formation (pick-up) and high tempurature (i.e above 600^0 c).
An apparatus called 'Scrapper' is installed in a molten metal plating line includes a blade pressed against a roll dipped in a

molten metal plating bath, in which a metal strip travels. The apparatus removes substances deposited on a surface of the roll. The apparatus also includes an arm for supporting the blade, and a screw member disposed above the plating bath so as to traverse it and moving along an axis of the roll in the bath for removing substances deposited on the roll in the molten metal plating bath. The blades used in scrapping are made of stellite 6A material. It continuously traverses a path within a fixed cycle time. The deposition of dross on surface is removed by the scrapper.

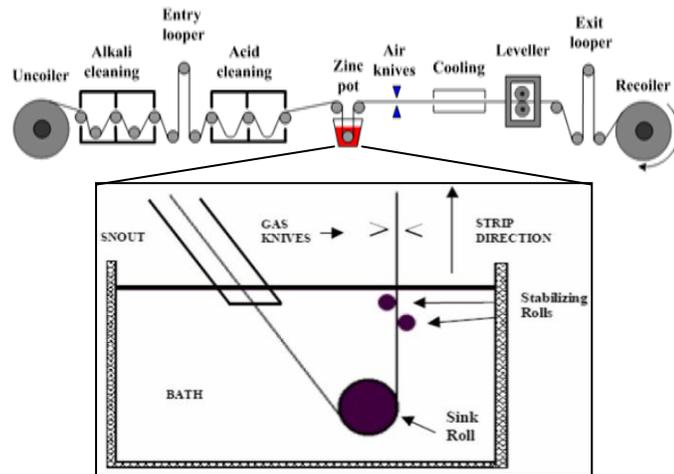The sink roll assembly is dipped in the Zn-Al pot in the Galvalume line setup as shown below:

Figure: Schematic representation for sink roll arrangement in Galvalume

The temperature of the main pot is about 600ºc - 610ºc. The CR sheet is coming from a vertical tubular arrangement called as 'Snout' and after wrapping over sink roll it passes for further processes to the next section of process line. Due to the pick-up problem on sink roll surface the sheets that are produced in plant are get downgraded.

Reasons for failure of sink roll:

➢ Vibrations in Assembly in operation while dipped in pot
➢ Side tracking from sink roll
➢ Sometime scrapping is improper resulting in impression on sheet
➢ Nucleation and growth of dross (Intermetallic compound) on roll surface

Numerous researchers have developed several static and dynamic tests to determine the corrosion of pot hardware materials in the galvanizing bath but information relating to the mechanism of dross formation on the roll surface has not been fully explained.[7]

The chemical reactions in pot are uncontrollable.The standard composition of the pot has to be constant throughout the process,so we have to find out the other alternative for minimizing the problems of galvalume so that the replacement time for assembly will increase.[8] The proper scrapping operation may avoid the downgrading of sheets in quality.

Chemical Reactions in pot

A heated metal pot contains a bath of molten zinc/aluminum. A continuous moving strip of low carbon steel is introduced into the bath from a furnace in the conventional manner. The strip passes around a sink roll and tensor rolls while submerged in the bath, so the surface of the strip picks up a zinc/aluminum coating. The strip is delivered to the bath through a conventional tubular snout. The interior of the snout housing contains an inert gas such as nitrogen or a mix of nitrogen and hydrogen to prevent oxidation of the steel strip.

Due to the extremely large dimensions of the equipment and in spite of efforts to prevent all possible air leaks into the furnace, small leaks do occur, generating ferrous oxides ($Fe_2O_3.FeO$, etc.) When the steel strip enters the bath, a chemical process occurs in which the melt in the bath reacts with the iron in the steel strip (inducing the coating) but also reacts with the oxides to form dross that contains ZnFe, ZnAlFe, $ZnFeAl_2O_3$, etc. The free iron settles to the bottom of the molten metal pot. Because of the slightly or nearly identical density to the molten metal, the oxides (Al_2O_3, ZnO) and the inter-metallics formed (ZnFe, ZnAlFe, etc.) remain in suspension or float to the surface in the form of dross. As the dross increases it gradually forms deposits on top of the sink roll and the strip being processed.

Standard rolls and equipment used in the hot dip metalizing process, when the alloy melt is zinc or zinc/aluminum with aluminum concentrations of less than 60%, are made of 316-L stainless steel. The rolls and bearings, in particular, require continuous maintenance of their surfaces. The rolls are removed weekly from the pot and their surfaces machined to remove accumulated dross, to smooth the roll surfaces as well as to return them to a round and straight condition. The main reason for this continuous maintenance is because 316-L stainless steel is not a material formulated specifically for this application and, consequently, it lacks the properties to meet the operational needs.[10]

In order of importance, although all requirements must be met to a minimum degree, the properties required for a proper roll material that meets the operational needs are as follows:

1. Very low solubility in molten zinc or zinc/aluminum alloys.
2. Low adhesion (Non-wettable) to zinc/iron and zinc/iron/aluminum dross.
3. High surface hardness (More than RC 40). Abrasive wear contributes nearly half of the loss of roll life in metalizing applications.
4. Dimensional stability at operating temperatures up to 700°C., for straightness and roundness. This property is necessary because of the difficulties encountered when the lines operate at over 100 RPM, generating excessive vibration and damage to the holding equipment.
5. Thermal shock resistance. The roll should be capable of withstanding a thermal shock of no less than 260° C. when going from air to the molten metal, and 700° C. when going from the molten metal to air.
6. Good impact and notch resistance strength. This is important due to the severity of the application.
7. Centrifugally castable and machinable by standard procedures in order to provide simple and available maintenance.
8. Economic viability.

It is important to understand the interaction of dissimilar metals in solid-liquid states. The joining of dissimilar metals in a solid-liquid state is governed by their physio-chemical properties and by the interaction between them; or, in the case of more complex systems, such as super alloys, by their interaction with all other alloying elements and impurities. When the melting point of the corrosive metal (the coating alloy in our case) is much lower than that of the metal being attacked (the roll material), the roll material may remain in a solid state throughout the process. In this case, a strong metallic bond between the atoms of the coating metal and the roll material occurs in the wetting process. It is true, however, that other associated processes can significantly influence the attack rate and kinetics of solubility, i.e., dissolution, interdiffusion and formation of intermetallics that have a significant effect on the bonding properties of the intermetallic layers being formed.

Experimental as well as theoretical findings have shown that the attack on a solid metal by zinc and zinc/aluminum alloys is a topo-chemical reaction in which a two-stage formation of strong bonds between atoms of the two materials is a characteristic feature.[10]

In the first stage, a physical contact is established by the close proximity of the two metals allowing interaction between the atoms. The electrostatic interaction between the surface atoms is of great importance at this stage.

In the second stage, the chemical interaction takes place and the formation of a strong bond is completed. At this stage, quantum processes between the electrons prevail. Thus, the occurrence of electron interaction of different types of materials requires a definite quantity of energy for surface activation. This energy, in the case of "hot dip" metalizing is imparted in the form of heat retained in the molten metal that is maintained at temperatures well above their melting temperature in order to improve the coating capability of the melt alloy in accelerated production. In other words, the lower the temperature of the melt in the pot, the slower the two basic stages of alloying formation.

In order to improve the resistance of ferrous alloys to molten aluminum, it is necessary to study the dissolution process that follows wetting in detail. The dissolution of solid ferrous alloys into molten aluminum has been studied by M. Kosaka and S. Minowa (Transactions Iron & Steel Institute of Japan, Vol. 50 and 52, 1964.) It is also theoretically described by Nernst-Shchukarev's equation

$$dc/dt = Ks\, A/V.(Cs - Ci)\ldots\ldots\ldots\ldots (1)$$

where,

Ci = the instantaneous concentration of the dissolved metal in the melt (weight percent)
Cs = the saturation concentration at operational temperature (weight percent)
Ks = the dissolution rate constant
A = the surface exposed to the Zn/Al melt
V = the volume of the melt

From this equation and assuming the dissolution of the solid metal is controlled by mass transfer into the molten metal, the rate in weight. loss of a roll submerged in the molten alloy is expressed by the equation

$$-dw/dt = Ks\, A(Cs - C)\ldots\ldots\ldots\ldots (2)$$

Where, t = time
Ks = dissolution rate constant

A = roll surface area exposed to the melt
Cs = saturation concentration of the melt at the operating temperature in weight percent
C = instantaneous concentration of the weight dissolved metal in the melt in weight percent
W = the weight of the roll

Since in a coating line the melt alloy is being added continuously, it can then be accepted that C=0 (or approximately zero)

In other words, the dissolution of the roll material into the melt depends on two elements:

1. Cs --A coefficient, independent of time, whose value can be obtained from the concentration of the liquidus curve at the operating temperature in the phase diagram for each of the components of the roll material.
2. Ks--A coefficient, dependent on time, that establishes the kinetics of dissolution of each one of the component elements of the super alloy roll material

Utilizing metals or transition metals with a Cs equal to 0 at the operating temperature of the melt, obtains a non-wetting, zero-solubility alloy for operation in the alloy melt. Unfortunately, only two such materials exist for zinc, namely, **tungsten** and **carbon**. Only one exists for aluminum, carbon.

It has then been necessary to study the dissolution coefficient, Ks, for metals and transition metals, and its change with changes in operating temperatures, velocity, etc. (N. Tunca, G. W. Delamore and R. W. Smith) (Metallurgical Transactions Association, Vol. 21A, November 1990) and to establish its variation in value for binary and ternary alloys (V. R. Ryabov) (Aluminizing of Steel, Oxonian Press Pvt Ltd N.D.)[16]

Due to the large quantity of experimental data needed and the scarcity of it, an attempt has been made to establish a correlation between the theoretical values of the dissolution coefficient, Ks, with the existing experimental values (Mitsuo Niinomi and Masamichi Sano). (Dissolution of Ferrous Alloys into Molten Aluminum, Transactions of the Japan Institute of Metals, Vol. 23, No. 12) Unfortunately, it was established that the kinetics of dissolution of metals and transition metal alloys in zinc/aluminum melts do not follow the **Nernst/Shchukarev** equation.

The differences of the coefficients Ks obtained should be attributed to:

1. The mechanism of dissolution (static, natural convection dynamic, etc.).
2. The relationship to the appearance and growth peculiarities of the intermetallic phases formed at the interface of the solid and liquid metals.

The growth of these intermetallic phases in zinc/aluminum alloy melts, as discussed earlier, is extremely fast. Their growth decreases the dissolution rate, and with C_s and A values constant, the value of K_s must decrease with time below the theoretical value. Finally, the dissolution process changes to an intermetallic layer/alloy melt diffusion controlled process. This occurs when the critical thickness of the intermetallic layer is reached and dissolution reaches equilibrium

Additional studies were conducted using V. G. Levich's equation in order to enter into consideration the rotational velocity of the roll.

$$dc/dt = 0.62\, S/V\, D^{2/3}\, v^{-1/8}\, w^{1/2}\, (Cs - Ci)\ldots\ldots\ldots (3)$$

where

Ci = the concentration of additive

Cs = the saturation concentration
T = the time
S = the surface area of the specimen
V = the volume of the aluminum/zinc melt
D = the diffusion coefficient
V = the kinematic viscosity
W = the angular speed of rotation

Equation (3) at t=C=0 and w=1 may be used to theoretically evaluate the diffusion of metals in molten metals. This effect was partially initiated and conducted with some degree of correlation by T. Heumann and S. Dittrich. (Z. Metallkunde, Vol. 50, 1959, p. 47-617).

A fourth approach undertaken to analyze the behavioral change of the diffusion coefficient utilizes the Stokes-Einstein formula. The difference between the coefficient obtained by the theoretical calculations with that reduced from experimental tests utilizing the theoretical formulae differ in value by 10 to 20 times, even though the techniques used in determining the coefficients in most cases were almost the same.

Perhaps the most valuable information is that derived from the following facts:

1. Aluminum and zinc do not attack or wet most oxides, carbides or nitrides.
2. At steady-state equilibrium, K_s is no longer a variable function of time ($K_s =f(t)$) but a constant.

The investigations (V. R. Ryabov, Alitirovanie Stali, Chapter IV, Metalurgiya Publishers Moscow) on how the addition and concentration of other elements to iron affected the diffusion zone, and formation of intermetallics and change in the dissolution rate, lead to the following conclusions:

Carbon

The structure of iron-carbon alloys formed by slow cooling from the γ-solid solution region is well known. Only the nature and the properties of the diffusion zone developed when immersing the prepared alloys in aluminum as a function of temperature, duration and the percentage of carbon content were studied.

With an increase in carbon content from 0.2 to 0.56% the thickness of the intermediate layer varies insignificantly at both 750° and 850° C. (from 110 to 125 and from 90 to 110 μm respectively). The layer has greater solubility at 850° C. and is, therefore, thinner, increasing the mass transfer rate.

In the interaction of aluminum with iron, when the latter has a body-centered cubic lattice α-Fe, the diffusion layer is always jagged towards the iron side. In the case of interaction of aluminum with iron or an alloy containing iron in a face-centered cubic, γ-Fe, the diffusion layer has smooth boundaries.

Nickel

The maximum nickel (and chromium) content in the alloys were the same as in stainless steel to examine the effect of each percentage element individually.

Nickel belongs to the group of those elements forming a continuous series of solid solutions with iron. Introduction of nickel into iron widens the γ-Fe region. Nickel has a low Cs in zinc, but it is very high in aluminum; and its addition is equivalent to an increase in temperature of the alloy melt.

Chromium

Chromium belongs to the group of alloying elements, which narrow the γ-region. The chosen chromium content and the aluminizing temperature do not alter the region of phase changes, as seen in the iron-chromium phase diagram.

Thus, the diffusion zone, formed in aluminizing, varied only as a function of the chromium content in the substrate alloy, temperature and duration of aluminizing.

Manganese

Manganese is one of the alloying elements which widens the γ-region, behaving very much like nickel. A continuous series of solid solutions does not appear in a solid state in the iron manganese system. Diffusion of manganese in α- and γ-iron is more difficult than the diffusion of carbon. The alloys prepared cross only through α- and α γ-region during aluminizing.

Silicon

Although silicon belongs to those elements which narrow the γ-region, it behaves in a more detrimental manner than nickel because of its high Cs in aluminum and the reduction of aluminum's melting temperature as the silicon percentage increases to 12.6% at the eutectic ratio. Silicon, if added to the aluminum bath, has a greater effect than increasing its content in steel. An increase of silicon in either the bath or steel reduces the hardness and thickness of the diffusion layer to the same extent. With an increase of silicon in steel, the silicon content in the diffusion layer increases.

Boron, Titanium, Vanadium and Molybdenum

Boron very strongly narrows the γ-region. Boron and carbon are the only elements with atoms small enough to fit into the interstices of iron crystals. The addition of these atoms (boron and carbon) creates a strong increase in the crystal's internal energy, strengthening the alloy and reducing its solubility in zinc/aluminum melts. Phase changes in iron-titanium alloys set in only above 900° C. An introduction of titanium in iron strongly narrows the γ-region. Vanadium and molybdenum drastically limit the γ-region. No phase changes took place at aluminum immersion temperatures tested with the selected molybdenum and vanadium content in the alloys .

From the kinetics formation of the diffusion layer and the growth thickness and properties of the intermetallic layers between solid-liquid phases, it can be concluded that if a metallic alloy must be formulated to resist zinc/aluminum melts, it should meet the following requirements:

1. The components of the alloy should have the lowest saturation concentration possible, i.e., $1\%>C_s =0$ at the metalizing operating temperature.
2. The alloying elements must narrow the γ-Fe region, and their percentage content should be such that only the γ-region is covered at the coating operational temperature.
3. The intermetallic layer thickness formed during molten zinc/aluminum immersion at steady-state conditions should not be less than $1.2×10^2$ μm.
4. Elements that reduce the melting temperature of either zinc or aluminum should not be used as components of the melt resistant alloy .
5. The formation of strong covalent bonded molecules of the type M_xC_y should be promoted to generate a microstructure

rich in hard and steady carbides, resistant to molten zinc/aluminum, having tough complex matrix structures.

The second requirement for a roll material requires it to be non-wettable to a zinc/iron or zinc/iron/aluminum dross. Surface phenomena as stated earlier plays a decisive role in the formation of strong bonds. Data and analyses performed by J. A. Morando strongly suggest that the work of adhesion of metals and transition metal alloys decreases with increases in the surface hardness and a reduction of surface energy of the adhesion resistant alloy. This is due perhaps to the fact that the surface hardness of the resistant alloy is a consequence of the concentrations of low surface energy carbides (WC, MoC, VC, etc.) present on the roll surface.

By formulating a material based on the restraints of the selected criteria, the mass transfer rate is reduced with the increase in complexity of the intermetallic layer and with a decrease in the bonding strength of the diffusion layer, as a consequence of the minimization of matrix exposure and reduction of exposed effective area. The carbides' surface coverage makes the dross adhesion by mechanical action less likely, since the strip running through the roll surface can easily remove it before it can build up to a detrimental thickness that affects the quality of the coating finish.

Surface Hardness

A high surface hardness (More than RC 40) is necessary. This is a mechanical requirement imposed by the fact that the roll surface is acting as the bearing surface for the steel strip being processed, and sliding friction between the two will occur during operation. The wear caused by this sliding friction can be greatly reduced if the material hardness is above RC 40. One of the many reasons for the poor performance of 316L stainless steel is the fact that it cannot be scraped to remove melt dross due to its very soft surface. On the other hand, if it could have been removed, it would fail even faster due to abrasive wear. 316L surface hardness is approximately RC 10 and highly inadequate.

Thermal shock resistance and impact resistance, can be achieved by proper utilization of nickel, iron and cobalt necessary to form the solid solution matrix that will contain the carbides as outlined in the discussion of the selection criteria.

Molten zinc/aluminum resistant advanced material formulation

A General Chemical Composition

Taking into consideration all the previous discussions included, we are now in a position to suggest the chemical composition limits of a super alloy material capable of resisting molten zinc/aluminum alloy melts and their drosses.

%	Component	%
1.9 <	C <	2.3
16.0 <	Cr <	24.0
0.0 <	Ni <	2.0
15.0 <	W <	25.0
4.0 <	Mo <	8.0
4.0 <	V <	6.0
0.0 <	Nb <	2.0
5.0 <	Co <	15.0
0.0 <	B <	2.0
35.0 <	Fe <	45.0
0.0 <	Zr <	6.0

Experimental rolls made in this fashion, have shown continuous operation without maintenance three to five times longer than standard materials and a total roll life of six to ten times that of standard materials.[10] Similar performance has been obtained from roll bearings manufactured of materials formulated in accordance with the suggested material alternative.

Description of the new formulation suggested

Ass discussed above and going through the various embodiments and the invention the following alloys material meets the operational needs in Galvalume :

AT101

Composition of AT101 (For Al ≥ 50 %) in percent by weight :													
B	C	Co	Cr	Mn	Mo	Nb	Ni	Si	Ti	V	W	Zr	Fe
-	2.2	15	18	1	4	-	-	-	-	-	10	–	45

The AT101 having hardness value RC 42 (i.e. more than RC 40). These rolls were prepared by centrifugal casting methods, tested for 30 days [10] and the results, measured in terms of alloy loss into the bath were as follows:

(ΔD) Diameter Loss Per Day Vs. Roll Material and Melt Composition

Roll Material of test Sample	Bath Melt Composition	
	Zn @ 500°C	45% Zn + 55% Al @ 600°C
316L	.762 mm/Day	.816 mm/Day
AT101	.0762 mm/Day	.0830 mm/Day

Conclusion

The Roll made by the material of new formulation results in better performance than the traditional roll made by SS316L . The Pickup of dross on the sink roll surface is minimized by the formation of inhibition layer on the surface of roll which minimizes the deposition on roll. Thus, the premature failures of sink roll and the downtime engaged with its replacement is minimized. It also tends to reduce frequent stoppages by failure of sink roll. Thus, the life of Sink roll in pot may increased from 2-4 days upto 20 days.

tremendous support, knowledge and encouragement and had the trust in my capability to the conduct the research of this nature.

References

1. Patent on Method of Manufacturing Hot-dip Galvanized sheet by Sang-Heon Kim,Yeong-Sool Jin.
2. Zinc-Pot Maintenance Services "Tungsten carbide/cobalt roll Coatings" by SMS MILLCRAFT Group.
3. Paper on " Progress In Development of Galvanizing Bath Management Tools " by N.Y. Tang, M. Dubosis, F.E. Goodwin.
4. Paper on " Utilizing Pumps To Remove Zinc Dross From Inside The Inlet Snout " by Gregory C. Becherer
5. Reasearch paper on "Improving the efficiency of galvanizing plant with optimizing Techniques" by Dilip Joshi,Richard Jige.
6. Sink role manufacturing by Yentai Chintiago Alloy Steel Pvt. Ltd.
7. Performance of Submerged Hardware in Continuous Galvanizing by N.Y. Tang, Daniel Liu, Keith Zhang.
8. "Dross formation mechanism on Stainless steel hardware in a Zinc-55%Al bath" by Ashok Varadrajan,Bruce Kang and Mark Bright.
9. Liquid Metal Corrosion of 316L in Molten Zn-Al Baths by Vinod Sikka Xingbo Liu.
10. Patent on "Material formulation for galvanizing equipement submerged in molten Aluminum and Aluminum/Zinc bath melts"
11. "Investigating Galvanneal Reactions on pot hardware material" by Mark Bright.
12. Loth, J., "Zinc Pot Bearing Design Modification for Increased Life", Galvatech 2004 Conference Proceedings, Chicago, IL, pp. 657-666
13. Yao M.X., Wu.J.B.C., Liu.R., "Microstructural characteristics and corrosion resistance in molten Zn-Al bath of Co-Mo-Cr-Si alloys", Materials Science and Engineering A 407 (2005) 299-305.
14. Liu, X., Barbero, E., Sikka, V., "Corrosion of Several Alloys in Industry
15. Dipping Baths", Galvatech 2004 Conference Proceedings, Chicago, IL,
16. pp.629-636
17. Essentials in Hot-Dip Galvanizing by Jason Fargotti
18. Hemrick, J.G., J. Xu, K. Peters, X. Liu, and E. Barbero. "Wetting and ReactionCharacteristics of Al2O3/SiC Composite Refractories By Molten Aluminum and Aluminum Alloy", International Journal of Applied Ceramic Technologies 4 (2007): 514-523.
19. K. Chang, G. Psaros, J.J. Brinsky, R.L. Nester, R. Carter, V. Sikka, "New Material Research and Life Improvement for Pot Hardware in Continuous Hot-Dipping Processes," Steel Industry of the Future.
20. Rabinowicz, Ernest, Friction and Wear of Materials, John Wiley & Sons, Inc., New York, 1995, pgs 239-250.
21. El-Madg, M.A. Shaker, R. Hechor, A.E. Nasser, Mechanical Behavior of Stellite 6 Produced by Powder. Metallurgicaly Process, 6th Int. Conf. On Mechanical Design and Production (mpd-6). Cairo, Egypt. 1996.
22. Machine Design: A CAD Approach, Andrew D. DiMarogonas, John Wiley and Sons,Inc., 2001
23. Use of Stabilizer Rolls for Strip Flatness While Wiping, Michel DuBois, 1998Galvanizer's Association Proceedings, October 1998
24. Reactions of Various Materials with a Galvanizing Bath, K. Zhang & N.-Y. Tang, 2003 Galvanizer's Association Proceedings, October 2003
25. Durability of Bath Hardware Materials in Continuous Galvanizing, M.S. Brunnock, et. al., 1996 Galvanizer's Association Proceedings, October 1996
26. Empirical Wear Rate Modeling of Zinc Pot Bearing Materials Using the WVU Small-Scale Tester, J. M. Snider II and J. L.Loth, 6th International Conference on Zinc and Zinc Alloy Coated Sheet Steels, April 2004