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Insight into the law and mechanism of selective oxidation of Q&P steel under different annealing parameters

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Abstract

In order to investigate the law and mechanism of selective oxidation of Quenching and Partitioning (Q&P) steel under different annealing parameters, the sensitivity of alloy elements added in Q&P steel to the annealing parameters was explored. Galvanizing experiments of QP steel were carried out at different annealing temperatures (770 °C and 730 °C) and different holding times (180 s and 300 s). The concentration change of selective oxidation element and the alloying element distribution in the coating were analyzed by Glow Discharge Optical Emission Spectrometer (GDOES), the morphology of surface oxides and inhibition layer were observed by Scanning Electron Microscope (SEM). The results showed that higher annealing temperature (770 °C) and longer annealing time (300 s) could both increase the concentration of Mn and Si on the surface of Q&P steel, improve the oxidation degree of steel surface, thin the inhibition layer, and lead to more leakage plating and deterioration of surface coating quality. The Mn depth profiles showing a parabolic trend and reaching its maximum value at about 20 nm below the surface, while the concentration of Si gradually decreases from the surface to the interior. The selective oxidation of Si and Mn are more sensitive to the annealing temperature than the annealing time.

1. Introduction

Q&P steel, as the representative of the third-generation high strength steel, has been used in various automobile parts now. Low alloy addition and good performance of strength and elongation make it well meet the comprehensive requirements of automotive steel [1–3]. For widely application, anti-corrosion treatment is often essential for prolong its service life. Hot-Dip galvanizing, which can improve the corrosion resistance of steel economically and effectively, is the most widely anti-corrosion technology of automobile steel. Unfortunately, the selective oxidation of alloying elements in Q&P steel would be an inevitable problem during the continuous annealing before galvanizing. Even though with a protective gas in annealing furnace, the alloying elements (mainly Si and Mn) in Q&P steel will also react with trace moisture or oxygen to form oxide particles or oxide film on the surface of steel plate [4–6]. These oxides are non-infiltrating with zinc liquid when galvanized, preventing the matrix surface from forming a compact inhibition layer. Inhibition layer is a barrier layer formed by adding trace amounts of Al in zinc bath to prevent the direct reaction between iron and zinc in zinc solution [7].

The prerequisite for a good coating is to form a compact inhibition layer, generally thought to be Fe3Al3−xZnx at the Zn/Steel interface [8, 9]. The inhibition layer grows on the pre-formed oxide surface in the molten zinc during the short galvanizing time (4–6 s) [10]. The purpose of adding Al into the molten zinc pool is to make Fe and Al react preferentially to form a dense inhibition layer and inhibit the formation of brittle Fe–Zn phase. However, the growth of inhibition layer depends largely on the status of surface oxides.
For sure, the selective oxidation of alloying elements on the surface of the steel plate is inevitable and it is essential to control the oxides state of the steel plate surface. The main factors affecting the selective oxidation of alloying elements are the original chemical composition of steel, annealing parameters, reducing gas environment of annealing furnace and dew point temperature \cite{11–14}. The ratio of Si/Mn in the original chemical composition of high-strength steel has great influence on the wettability of zinc plating. It has been suggested that the Si/Mn ratio below 0.5 would be a safe value \cite{15}. Besides, the sensitivity of Si and Mn to annealing parameters is greatly different, which will both affect the degree of selective oxidation. Generally, due to the performance requirements of different high strength steels, the content of important alloy elements has a default range. Therefore, the sensitivity of alloy elements of different high strength steels to annealing parameters will vary greatly. In a medium-Mn steel containing 6% Mn and 2% Si, the state of surface oxide layer presents thick film after annealing at 800 °C, while the distribution of surface oxide layer is sparse and thin when annealing at 600 °C for 120 s \cite{16}. However, the situation occurs in the higher-Mn-content Twinning-Induced Plasticity Steel (TWIP) is different. Scholars had found that the internal MnAl2O4 will become rougher after heating the annealing temperature of Al-added TWIP steel from 700 °C to 800 °C. Meanwhile, it also grows some large MnO in the interior and produces some ferrite free of oxides under the exterior MnO, the amounts of ferrite increases with the rising of temperature \cite{17}.

In a whole, the selective oxidation of high strength steels with different alloy contents is quite different. Meanwhile, the selective oxidation of third-generation high strength Q&P steel has received little attention. The low Si and Mn content will make the selective oxidation of Q&P steel different from that of medium Mn steel and TWIP steel. The aim of the present study is to investigate the sensitivity of alloy elements added in Q&P steel to the annealing parameters (annealing temperature and annealing time) and its influence on the wettability of Q&P steel. In addition, the mechanism of selective oxidation of elements under different conditions will be revealed. This is also the first time in the published article that combining the Q&P process with industrial galvanizing process, attempting to simulate the real industrial Q&P steel continuous galvanized process.

2. Experimental procedures

The Q&P steel used in the experiment is cold rolled. The main chemical elements are: 0.18 C, 1.49 Si, 1.55 Mn, 0.046 Al (mass fraction/\%). The size of galvanized coupon is 220 × 110 mm with a thickness of 1.2 mm. The length direction is the same as the rolling direction of the steel. The coupons of selective oxidation are grinded with 4000 grit SiC paper before galvanizing to prevent the influence of surface roughness on the experimental results. Finally, the coupons were wiped with alcohol and acetone respectively before galvanizing. The simulated galvanizing experiment was carried out on the IWATANI hot dip galvanizing simulator at a 25% H2–N2 mixed atmosphere. The continuous annealing hot dip galvanizing schematic is shown in figure 1. The coupon first heated to partial austenitizing temperature (730/770 °C) holding for a while (180/300 s), followed by a rapid cool to a quenching temperature 200 °C at a speed of 20 °C s−1, the partitioning temperature was 400 °C, after partitioning, the coupon was heated to a temperature that slightly higher than the galvanized temperature and holding for 20 s to equalize the overall temperature through the coupons, then dipped into a 460 °C zinc bath for
The galvanized part has been enlarged in the upper right corner of figure 1. The whole process assumes that the galvanizing part is located after partitioning.

The process parameters of simulation experiment of continuous annealing hot dip galvanizing of Q&P steel are list in table 1. Three experimental steels under different parameters are labeled as No. 1, No. 2 and No. 3, respectively. The annealing atmosphere and dew point temperature used in the experiment are same. Obviously, the difference between No. 1 steel and No. 2 steel is the annealing time, and the difference between No. 1 steel and No. 3 steel are the annealing temperature.

The macroscopic morphology of the surface after galvanizing was photographed and observed by laser confocal microscopy. The zinc layer was removed by 10% fuming nitric acid, which can only retained the Fe–Zn–Al phase [18]. The surface morphology of oxides and inhibition layer under different conditions were characterized by Zeiss Field-SEM in the secondary electron mode. All the SEM samples require carbon spraying before observation. The growth and enrichment of alloy elements in galvanized layer were characterized by GDOES (GD PROFILER2). Meanwhile, the GDOES was also used to observe the alloy elements concentration-depth profiles within 1um below the surface, etching with Ar plasma at a 4 mm diameter analysis area.

### 3. Results

The macroscopic morphologies of galvanized coupons under different conditions are shown in figure 2. By comparing No. 1 and No. 2, it can be found that the surface quality decreases with the increase of annealing time, and the leakage plating increase obviously, indicating that the increase of time will reduce the wettability of galvanized sheet. Moreover, defects on the surface of galvanized samples with high annealing time appear to be large, almost all of which are distributed in the center of the pattern. For the situation of annealing temperature (No.1 and No.3), the surface quality of the coating increases to a certain extent after slightly decrease the annealing temperature and the surface leakage plating is less.

Through the laser confocal photographs of coating microstructure formed under different conditions in figure 3, it can observe that different annealing temperature and annealing time have little influence on the microstructure of galvanized layer, the particle distribution of galvanized layer is not uniform, and no good dendritic structures are formed, which are the symbol of a good coating [19]. The coating chemistry, grain size, surface morphology and crystal-logicraphic texture of the coating layer all can influence the quality of the galvanized coatings.
The cross-section images of each sample are shown in figure 4. Obviously, the coating of No.2 is thinnest, the coating of No.1 and No.3 is slightly thicker, and the coating thickness of No.1 is slightly thicker than that of No.3. However, the coating of No.1 has many internal defects and is extremely uneven.

Significant Al enrichment can be observed in the coating under each condition in figure 5, indicating that the formation of inhibition layer is present under every condition. The Al concentration of No.2 steel is significantly lower than that of the other two conditions, and the range of Al is small. This is consistent well with the conclusions obtained in some previous literatures [20]. Higher Al content is very beneficial to the formation of a good inhibition layer. The default point of intersection of zinc and iron is the thickness of the coating. Thus, the thickness of No.1 steel is the largest among the three coupons, while the thickness of inhibition layer of No.3 steel is slightly higher than that of No.2 steel. These results are consistent well with the cross-section observations of the three samples in figure 4. In addition, the concentration of Mn in the coating increases continuously and the content reaches the highest near the contact surface between the coating and the steel matrix, which means that the Mn element inside the steel matrix has diffused to the surface. The content of Si is relatively low, which can be further studied by surface oxides in the below.

The oxide and steel matrix show different color contrast values in the figure 6 and the white area corresponds to the oxide area [21]. The higher temperature and longer time has the highest oxidation degree by comparing the microstructure of oxide on galvanized coupons of the three different conditions. In their enlarged view, there are many granular oxides on the surface of No. 3 steel, but almost all the oxides of No.2 steel are in the form of overall blocks, and the oxides on No. 1 steel is in the form of smaller blocks and particles. Apparent, the
morphology and distribution of surface oxides of surface oxide have great influence on the formation of surface inhibition layer.

The inhibition layers generated under the three conditions are different. It can be seen from the macro photos of the inhibition layers, in figures 7(a), (c), (e)), that the inhibition layer of No. 3 steel is the densest, followed by No. 1 steel, and No. 2 steel has the most sparse inhibition layer with most bare substrates. This feature can be observed more clearly in the magnified images in figures 7(b), (d) and (f), the inhibition layer of the No. 3 steel has the best densification, while the No.2 steel inhibition layer has many large visible naked areas, and the density of No.1 steel lies between them. Furthermore, the particles of the inhibition layer of No. 3 steel are also the smallest. According to the previous literature, the particles are mainly composed of Fe–Zn–Al intermetallic compounds, and a good inhibition layer is also a necessary condition for the formation of a good zinc layer [22].

4. Discussion

Oxides formed on surfaces under different annealing temperature and annealing time is quite different (figure 6). Compared with the traditional steel, the advanced high-strength steel is more prone to selective oxidation during continuous annealing for its higher alloying elements. The steel reacted with trace amounts of water vapor and oxygen during annealing, which are not enough to oxidize Fe, but enough to oxidize the alloying elements in the steel. The distribution of oxidized alloying elements on the surface of the steel plate has a great effect on the wettability of the coating. Figure 8 lists the concentration of alloying elements within 1μm below the surface under each condition. Apparently, the main enriched elements on the surface are Si, Mn, O and Fe, and the concentration of each alloying element varies greatly.
For the different annealing time (figures 8(a) and (b)), the main enriched element within 20 nm below the surface is Mn, and there is obvious external oxidation under both conditions. The content of Si gradually decreases with the increase of depth, indicating that a part of Si on the subsurface has moved to the surface, and the large fluctuation in the second half of the curve shows that the distribution of Si-containing oxide in the depth profiles is relatively random. In detail, the concentration of the each elements in the range of 0–20 nm on the surface are quite different. In the depth of 0–10 nm below the surface, both galvanized samples was dominated by the enrichment of Mn and increased continuously from 0 to 10 nm. In contrast, the concentration of Si decreased slightly at 0–10 nm and then has a slight increase. While the concentration of O reaches the highest value at 10 nm below the surface, and Si is relatively low at this depth. The decrease of Si concentration is mainly due to the continuous increase of Mn. In the condition of this article, the oxides in steel are mainly expected to be SiO$_2$, MnO, MnSiO$_3$, Mn$_2$SiO$_4$ [16]. Sometimes, the Mn/Si atomic ratio of the oxides did not fit well with these well-known oxides. Although the annealing time is different, the main enrichment oxides in the surface layer under the two conditions are Mn oxides and Si-Mn intermetallic compounds.

For the different annealing temperatures (No.1 and No.3), the composition and concentration of alloying elements on the surface changed with the decrease of temperature. The dominant element in the surface of No.3 steel is changed to Fe, but the trend of O is still similar with No.1 steel. At the peak of O content, the content of Mn is lower than O, indicating that there are not only a large number of Mn-containing oxides but also other oxides such as MnO or (Mn, Fe)O on the surface of steel [23]. The iron dissolved in Mn oxide should be metal-bound iron and evenly distributed in Mn oxide.

To observe the variation trend of each element under different conditions more intuitively, the depth profiles of each element under different conditions are listed in figure 9. Comparing the No.1 and No.2 steel, it is
clearly that longer annealing time results in higher concentration of Mn throughout depth profile and the difference becomes greater in the period of 60 nm–90 nm. Both of the concentration trends of Mn take on a parabolic shape, with the vertex near 20 nm close to 40 at%. After that, it gradually decreases to a stable value. For the situation of Si (figure 9(b)), the profiles of Si have many fluctuations compared to curve of Mn, indicating that the distribution of Si oxides is not continuous over a large area. This phenomenon may contribute to the fact that Si often aggregates at grain boundaries in the form of SiO2, and similar appearance is mentioned in the continuous galvanizing process of 0.1C-6Mn-2Si high strength steel, the Si was generated at grain boundary and a Si-containing core structures with Mn was formed in the subsequent process [24]. Furthermore, the platform after 80 nm illustrated that the Si diffuses from the inside to the outside under both conditions.

With a longer annealing time, the No.2 steel can obtain more energy for the diffusion of alloy elements to the surface, especially pass through the grain boundary or the internal defect. The consequences caused by the diffusion of these alloy elements can be well observed in figures 6(a)–(d). In particular, the presence of Si-containing oxides on the surface is the most detrimental to obtaining a good coating, which is the most stable oxides in performance and difficult to be eliminated. The oxides form of Si is mostly film-forming oxides, such as a-xMnO.SiO2 (x < 0.9) and a-SiO2 oxides, leads to a deterioration of the wettability of the annealed steel and prevents the formation of the Fe2Al5−xZnx inhibition layer at the steel surface [25]. The oxidation of No.2 steel is more serious, which leads to an extremely poor growth of the inhibition layer with many exposed areas (figures 7(c), (d)), and eventually resulting in more leakage plating of No. 2 steel (figures 2(a), (b)).

With the different annealing temperatures (No.1-No.3), the changes in the concentration of Mn under the two temperatures is tend to be same, showing a parabolic trend and reaching the maximum value at about 20 nm below the surface. There is a large difference, approximate 20%, between the two steels at the maximum value. This is also the maximum concentration difference between the two steel. After that, the gap between the two curves gradually narrowed. The concentration of Mn of No.3 steel is lower than that of No. 1 steel in the whole

Figure 7. Morphology of inhibition layer formed under different conditions (a) No. 1 (b) Enlarged view of No.1 steel (b) No.2 (d) Enlarged view of No.2 steel (e) No.3 (f) Enlarged view of No.3 steel.
profile depth. Similarly, the concentration of Si of No. 3 steel was significantly lower than that of No. 1 steel in the whole depth profile. In particular, not only the concentration of Si of No. 3 steel is less, but also less fluctuation of the curve have, showing that the element Si does not accumulate in large quantities at grain boundary or other detect place.

The internal mechanism of profile distribution of Si and Mn under different annealing temperature can be explained as following. According to the following formula (1) provided by Huin [26], different annealing temperatures will produce different oxygen partial pressure gas environments.

\[
\frac{1}{2} \log_{10} P_\text{O}_2 = 3.00 - \frac{13088}{T} + \log_{10} \left( \frac{P_\text{satH}_2\text{O}}{P_{\text{H}_2}} \right)
\]  

Figure 8. The depth profiles of alloying elements under different conditions (a) No. 1 (b) No. 2 (c) No. 3.

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The \( T \) (K) is the temperature in formula (1). The \( P_\text{H}_2 \) and the \( P_\text{satH}_2\text{O} \) are the partial pressure of hydrogen and the saturation vapor pressure of H\(_2\)O in atm, respectively. According to formula (1), raising the annealing temperature will increase the oxygen partial pressure of the environment, higher oxygen partial pressure will make more flux of oxygen diffusion to the inside. Therefore, more alloy elements will be oxidized in the inside instead of the outside and the coating quality will be improved. At the same time, the formation and growth of oxides at the surface are controlled by oxidation kinetics, the nucleation rate of oxides will increase with the increase of temperature, that is, the amount of oxides formed on the surface of steel plate will increase. Meanwhile, the annealing temperature rising will prompt more element diffusion to the grain boundary and more elements can quickly spread to the surface through the grain boundary.

In general, the joint action of the two mechanisms determines the distribution and concentration of alloying elements on the surface. Obviously, the latter mechanism plays a dominant role. In consequence, the oxidation of No.1 steel is more serious than the No.3 steel (figures 6(a), (b)), and the oxides amount of No.3 steel are less and almost distribute on the surface in a granular form (figures 6(e), (f)). The dispersed oxides make the densification of the inhibition layer better (figures 7(e), (f)). Finally, the macroscopic coating of No.3 steel is slightly better than that of No.1 steel with less leakage plating on its surface.

Moreover, the diagram of O profile in figure 9(c) can also supports the above analysis. It has pointed out in the literature that the oxidation depth was corresponding to the value of the X axis of the half of maximum
The oxidation depth under the three conditions has plotted with lines of the same color as the respective curves in figure 9(c). The oxidation depths from No.1 to No.3 are 23.5 nm, 24.6 nm and 19.2 nm, respectively. Comparing the No.1 and No.3 steel, the oxidation depth of No.3 steel is obviously smaller than No.1 steel due to its lower annealing temperature. While the oxidation depth of No.2 steel with longer annealing time is slightly deeper than No.1 steel. It should be noted that, slight changes of annealing time and annealing temperature in this experiment, annealing temperature brings more obvious changes to the oxidation of steel plate. The figures 8(a), (b) also shows that the difference between No. 1 and No. 3 steel within 20 nm below the surface is significantly greater than the difference between No.1 and No.2 steel, indicating that the selective external oxidation of Si and Mn may be more sensitive to the annealing temperature.

As mentioned above, the quality of the coating depends not only on the amount of oxides, but also on the morphology, distribution and types of oxides. In the short process of galvanizing, excellent coating can be obtained by a series of mechanisms, including the aluminothermic reaction mechanisms, which is the reaction between Al dissolved in zinc solution and the MnO formed in the matrix [28], the bridging mechanisms between oxides with large gaps [29], the thermal stress mechanism of crack caused by different thermal stress between oxides and matrix during the rapid cooling process, and the oxide-lift-off mechanisms [30]. Nevertheless, the results of this article also show that it is a big challenge to obtain a good coating of Q&P steel. However, the effect of annealing temperature and annealing time on plating quality of Q&P steel discussed in this paper can be used as a reference for the industrial production of Q&P steel.

5. Conclusion

After galvanizing Q&P steel under different annealing conditions and characterizing the surface and inhibition layer by a series of experiments, the following basic conclusions are drawn:
(1) The concentration of Mn and Si on the surface of Q&P steel increase by either raise the annealing temperature (from 730 °C to 770 °C) or prolong the annealing time (from 180 s to 300 s). Both of them will increase the amount of oxides on the surface and the bare range of the inhibition layer. Eventually, the leakage plating of steel plate increased and the coating quality deteriorated.

(2) Slight change in annealing time and temperature have no influence on the concentration trend of Si and Mn in Q&P steel. The concentration trend of Mn approximates a parabolic shape with the vertex near 20 nm. While the concentration of Si decreases from the surface to the inside, and the depth profiles of Si fluctuated greatly at the annealing temperature of 770 °C due to the precipitation of Si at the grain boundary.

(3) The selective oxidation of Si and Mn is more sensitive to the annealing temperature than the annealing time in Q&P steel. The oxidation depth corresponding to 770 °C and 300 s is higher than that of the 730 °C and 180 s, respectively.

(4) Longer annealing time (300 s) makes the steel obtain more energy for the diffusion of alloy elements to the surface. Higher annealing temperature (770 °C) increases the oxygen partial pressure and make more flux of oxygen diffusion to the inside. Meanwhile, both can control the nucleation rate of oxides. The comprehensive result is that the oxidation of steel plate is more serious.

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References

[1] Meesen M, Zardet L, Homborg A M, Lekka M, Andreatti F, Fedrizzi L, Boelen B, Mol J M C and Terryn H 2020 Corr Sci. 137 108780
[2] Gong L, Jia J, Xiong W, Cheng Z Y and Bi Y J 2020 Surf. Eng. 36 706
[3] Yang H L, Zhang S G, Li L, Liu X and Wang H 2014 Surf. Coat. Tech. 240 269
[4] Huang F, Chen Y, Hua L, Zhou J X, Wang Z and Fang F 2019 Ironmak Steelmak 46 529
[5] Lin K and Lin C S 2014 ISIJ Int. 54 2380
[6] Fushiwaki Y, Nagataki Y, Nagano H, Tanimoto W and Sugimoto Y 2013 Tetsu-to-Hagane 99 221
[7] Cho L, Lee S J, Kim M S, Kim Y H and De Cooman B C 2013 Metall Mater Trans A 44A 362
[8] Song G M, Vystavel T, Pers N V D, Hosson J T M D and Stoof W G 2012 Acta Mater. 60 2973
[9] Hsu C W, Wang K K, Chang L, Gan D S, Chang Y L, Liang H Y and Wang H P 2018 Mater. Chem. 137 189
[10] Norden M, Blumenau M, Wuttke T and Peters K J 2013 Appl. Surf. Sci. 271 19
[11] Takada Y, Shimada S, Lee J, Kurosaki M and Tanaka T 2009 ISIJ Int. 49 100
[12] Yang T, He Y L, Chen Z, Zheng W S, Wang H and Li L 2020 Coatings 10 1
[13] Pourmajidi M and McDermid J R 2018 Surf. Coat. Tech. 357 418
[14] Suzuki M, Fushiwaki Y, Okumura Y and Tanaka T 2020 Metall Mater. Trans. B 51 467
[15] Suzuki Y, Yamashita T, Sugimoto Y, Fujita S and Yamaguchi S 2009 ISIJ Int. 49 564
[16] Pourmajidi M and McDermid J R 2018 ISIJ Int. 58 1635
[17] Jin X Y, Zong Y, Wang L and Wang H 2020 Surf. Coat. Tech. 386 125479
[18] Oh J, Cho L, Kim M, Kang K and De Cooman B C 2016 Metall Mater Trans A 47 5474
[19] Kim S G, Huh J Y, Chung G J, Hwang H S and Kim S H 2019 Metall Mater Trans. A 50 1186
[20] Cho L, Jung G S and De Cooma B C 2014 n Metall Mater Trans. A 45 5158
[21] Samanta S, Halder A K, Deo Y and Guha S 2019 Surf. Coat. Tech. 377 124908
[22] Kim M S, Kwak J H, Kim J S, Liu Y H, Gao N and Tang N Y 2009 Metall Mater Trans A 40 1903
[23] Blumenau M, Norden M, Friedel F and Peters K 2011 Surf. Coat. Tech. 206 559
[24] Seyed Mousavi G and McDermid J R 2018 Metall Mater Trans. A 49 1
[25] Cho L, Kim M S, Kim Y H and De Cooman B C 2014 Metall Mater Trans. A 45 4484
[26] Huin D, Flauder P and Leblond J B 2005 Oxid. Met. 64 131
[27] Cho L, Lee S J, Jung G S, Suh D W and De Cooman B C 2016 Metall Mater Trans A 47 1705
[28] Kavitha R and McDermid J R 2012 Surf. Coat. Tech. 212 152
[29] Bellhouse E M and McDermid J R 2011 Metall Mater Trans A 42 2753
[30] Sagl R, Jarosik A, Stifter D and Angeli G 2013 Corr Sci. 70 268