Effect of grain size on the corrosion resistance of low carbon steel

Maryam Soleimani, Hamed Mirzadeh © and Changiz Dehghanian
School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, PO Box 11155-4563, Tehran, Iran
E-mail: hmirzadeh@ut.ac.ir

Keywords: low carbon steel, corrosion, mechanical properties, grain boundaries

Abstract

Systematic works on the effect of grain size on the corrosion resistance of low carbon steel are scant. In the present work, a spectrum of grain sizes was obtained by simple heat treatment routes in a typical low-carbon steel. It was revealed that two distinct stages for the dependency of corrosion current density ($i_{\text{corr}}$) on the grain size exist. Above a limiting average grain size of ~22 μm, $i_{\text{corr}}$ decreased slowly with increasing grain size. However, below this limiting value, $i_{\text{corr}}$ increased rapidly, which was related to the increased density of grain boundaries as interpreted by theoretical calculation of number of grains per unit area. Conclusively, a grain size of ~22 μm (ASTM grain-size number of 8) was considered to be an optimum value according to the mechanical and corrosion standpoints.

1. Introduction

It is well known that the mechanical performance of low carbon steel is largely determined by the ferrite grain size, where finer grain sizes are favorable for mechanical properties [1–4]. However, due to the higher energy and chemical activity of grain boundaries, a high density of these boundaries increases the reactivity of the surface through increased electron activity and diffusion [5, 6], and hence, it can affect the corrosion resistance. Higher corrosion resistance performance results in longer service of the steel structures [7–10]. Therefore, studying the effect of grain size on the corrosion resistance of low carbon steel is an important subject.

A general consensus regarding the grain size effect on corrosion resistance of ferrous alloys is not available. If the coarse grained sample shows an active behavior in an electrolyte, then grain refinement will likely make the surface more active. However, when it shows passive behavior, grain refinement will likely results in a more stable protective film [6]. The energies of grain boundaries and triple junctions are higher than that of the bulk and there is an enhanced electron activity and diffusion rates, and hence, grain refinement enhances the reactivity of the surface [5].

Since the grain size variation can be achieved using a number of different approaches, the processing route effects on the microstructural features, in addition to grain size change, can also affect the corrosion properties via introducing internal stress, texture, etc [5]. Therefore, it is required to produce the variation of grain sizes based on the similar processing routes. In this regard, there are very few systematic studies on a spectrum of grain sizes for these steels. For HSLA steel, Chen and Zhang [7] observed that via grain refinement, the corrosion rate did not change noticeably when the grain size was greater than a limiting value; but at finer grain sizes, it increased rapidly. However, the reason behind this two-stage corrosion behavior with respect to grain size was remained unsolved and needs to be scientifically addressed.

Accordingly, the present work is dedicated to unraveling the effect of grain size on the corrosion resistance of low carbon steel based on a systematic study.

2. Experimental details

To develop a wide range of ferrite grain sizes, sheets of 0.12C-1.11Mn-0.16Si (wt%) steel were austenitized at 1050 °C for the holding times of $t$ (between 1 and 240 min) followed by (I) air cooling (normalizing, denoted as Nt) or (II) furnace cooling (full annealing, denoted as Ft). After etching in the 2% Nital solution, optical
micrographs were taken and the average grain size was obtained based on the intercept method. Vickers hardness test was based on the load of 5 kg. Subsize ASTM E8 specimens were tensile tested at room temperature under the constant cross-head speed of 1 mm min$^{-1}$. These tests were repeated once to insure the reproducibility of the results. A Solartron potentiostat (Model SI 1287) operating at the scanning speed of 2 mV s$^{-1}$ was used for corrosion tests in a 3.5 wt% NaCl solution at room temperature, which was based on the three electrode configuration (saturated calomel and platinum as counter and reference electrodes, respectively). These corrosion tests were repeated twice and it was found that the reproducibility of the results was in the valid range.

3. Results

Figures 1(a) to (d) depict the representative normalized microstructures. It can be seen that the samples have ferritic-pearlitic microstructures, which is consistent with the microstructure of similar steels [11–16]. By increasing the holding time at the austenitization temperature, the microstructures became coarser. This is related to the effect of austenitization time on the grain growth of austenite, and hence, coarser grain sizes were obtained during decomposition of austenite as also shown in previous works [17–20]. Figures 1(e) to (h) shows the microstructures of fully annealed samples, where as a result of slow furnace cooling, coarser ferritic-pearlitic microstructures can be seen compared to the air cooled normalized samples. Again, an increased holding time resulted in a coarser grain size.

For each micrograph, the volume fraction of pearlite was determined by image analysis from the surface fraction of this phase in the 2D micrographs. For the fully annealed and normalized samples, the average amount of pearlite was obtained as 15.1 ± 3 and 14.8 ± 2 vol%, respectively. On the other hand, the size of pearlite colonies and their distribution are dependent on the processing route, where the pearlite colonies are refined and show more uniform distribution in the normalized samples. However, these morphological aspects also highly depend on the average grain size, where for the N240 (figure 1(d)) and F120 (figure 1(g)) samples with a comparable grain size, the size of pearlite colonies and their distribution are relatively similar. Therefore, it seems that the main microstructural parameter is the average grain size.

The summary of grain size measurements is shown in figure 1(i). It can be seen that the average grain size of N1 and N240 samples is ~11.5 and 46.3 μm, respectively. Larger grain sizes were obtained for fully annealed samples, where the average grain size of F120 and F240 samples is ~47.6 and 70.0 μm, respectively. Therefore, grain sizes in the range of 11.5 to 70.0 μm were obtained.

The measured hardness values of the samples are shown in figure 2(a), where it is seen that, by increasing the grain size, the hardness falls rapidly. The effect of grain size ($D$) can be better visualized by the Hall-Petch plot as
shown in figure 2(b). It can be seen that the data follows a straight line in the hardness versus $D^{-0.5}$ space for both normalized and fully annealed data and the Hall-Petch relation of $H = 240.7 / \sqrt{D} + 80.8$ can be obtained.

Some representative polarization curves are shown in figure 3(a), where the corrosion current density ($i_{corr}$) was obtained by the Tafel extrapolation method [21–28] according to the anodic and cathodic extrapolation lines shown in figure 3(a). The results are summarized in figure 3(b), where by grain refinement, it can be seen that $i_{corr}$ firstly increased slowly but increased rapidly afterwards. It should be noted that the line fitted to the first stage includes the data from both normalized and fully annealed samples ($y = 3.60 - 0.029x$). By consideration of separate regression analysis, the fitted lines of $y = 3.68 - 0.031x$ and $y = 3.51 - 0.027x$ can be obtained for the normalized and fully annealed data, respectively. It can be seen that there is a relatively good agreement between these fitted lines, and hence, the normalized and fully annealed data can be considered simultaneously.

4. Discussion

It was generally seen in figure 3(b) that by grain refinement, $i_{corr}$ increases. This can be directly related to the effect of grain boundaries [7–10]. Due to the higher energy and chemical activity of grain boundaries, a high density of these boundaries increases the reactivity of the surface through increased electron activity and diffusion [5, 6]. However, there is a new finding in the present work, where by grain refinement, it can be seen that $i_{corr}$ firstly increases slowly but then increases much more rapidly. This needs to be elaborated.

Since the corrosion test is applied to a constant surface area of the samples, a finer $D$ results in a higher density of grain boundaries, which can be simply represented by an increase in the total number of grains available in that constant surface area (figure 3(c)). This implies that the number of grains per square centimeter ($G_{cm}^2$) versus grain size is a good measure to study the effect of grain size on the corrosion behavior. If the grains are simply considered as cubes with an edge of $D$ (i.e. the average grain size), in the two-dimensional micrographs, a square with an edge of $D$ can be seen, where $D$ is expressed in $\mu m$. Therefore, the area of each grain is $D^2$. Now, $G_{cm}^2$ can be calculated as $10^6 / D^2$. The plot of $G_{cm}^2$ versus $D$ is shown in figure 3(d). It can be seen that by grain refinement, $G_{cm}^2$ firstly increases slowly up to $\sim 20 \mu m$, but then in the second regime, it increases.
much more rapidly. Therefore, in the second regime, due to the very high density of grain boundaries, the reactivity of the surface increases significantly.

Therefore, it is evident from the experiments (figure 3(b)) and theoretical calculations (figure 3(d)) that two regimes for grain size dependency of corrosion properties on the grain size are available, which are shown in figure 3(b). It can be seen that the data can be fitted by two straight lines, where these lines coincide at the grain size of 21.7 μm. Therefore, 21.7 μm is a critical grain size below which the corrosion properties deteriorate rapidly. On the other hand, larger grain sizes are not desirable from the standpoint of mechanical properties (figure 2(a)). Figure 2(c) depicts the tensile stress-strain curves of the N60 and F240 samples with grain sizes of ~20.5 and ~70 μm, respectively. While the corrosion resistance of N240 is better than that of N60 sample (figure 3(b)), it can be seen in figure 2(c) that the tensile strength of N60 is ~50 MPa higher than that of N240. Conclusively, the grain size of ~22 μm (ASTM grain-size number of 8) is desirable both from mechanical and corrosion standpoints.

5. Conclusions

In this work, a spectrum of grain sizes was obtained by simple heat treatment routes in a typical low-carbon steel and the effect of grain size on the corrosion resistance was studied. The following conclusions can be drawn:

1. The hardness and tensile strength decreased with increasing the average grain size. As a result, a Hall-Petch relation of $H = 240.7 / \sqrt{D} + 80.8$ was obtained to relate the hardness with average grain size.

2. Grain refinement resulted in the increase of corrosion current density ($i_{corr}$). This was related to the higher energy and chemical activity of grain boundaries, which increases the reactivity of the surface through increased electron activity and diffusion.
(3) Two distinct stages were identified for the dependency of corrosion current density ($i_{\text{corr}}$) on the grain size. Above a limiting average grain size of ~22 $\mu$m, $i_{\text{corr}}$ decreased slowly with increasing grain size. However, below this limiting value, $i_{\text{corr}}$ increased rapidly, which was related to the increased density of grain boundaries as interpreted by theoretical calculation of number of grains per unit area.

(4) A grain size of ~22 $\mu$m (ASTM grain-size number of 8) was considered to be an optimum value according to the mechanical and corrosion standpoints.

Acknowledgments

The authors would like to greatly thank the members of the ‘Advanced Steels and Thermomechanically Processed Engineering Materials Laboratory’ and the ‘Coating and Corrosion Lab’ for their help and support. Financial support by the University of Tehran is also gratefully acknowledged.

ORCID iDs

Hamed Mirzadeh https://orcid.org/0000-0001-7179-0052

References

[1] Armstrong R W 2014 60 years of Hall–Petch: past to present nano–scale connections Materials Transactions 55 2–12
[2] Liu M Y, Shi B, Wang C, Ji S K, Cai X and Song H W 2003 Normal Hall–Petch behavior of mild steel with submicron grains Mater. Lett. 57 2798–802
[3] Hall E O 1951 The deformation and ageing of mild steel: III discussion of results Proc. Phys. Soc. London, Sect. B 64 747–53
[4] Nouroozi M, Mirzadeh H and Zamanj M 2018 Effect of microstructural refinement and intercritical annealing time on mechanical properties of high-formability dual phase steel Materials Science and Engineering A 736 22–6
[5] Ralston K D and Birbilis N 2010 Effect of grain size on corrosion: a review Corrosion 66 075005
[6] Ralston K D, Birbilis N and Davies C H J 2010 Revealing the relationship between grain size and corrosion rate of metals Scr. Mater. 63 1201–4
[7] Chen Y T and Zhang K G 2012 Influence of grain size on corrosion resistance of a HSLA steel Advanced Materials Research 557 143–6
[8] Soleimani M, Mirzadeh H and Dehghanian C Unraveling the effect of martensite volume fraction on the mechanical and corrosion properties of low carbon dual phase steel Steel Res. Int. 1900327 in press
[9] Li Y, Wang F and Liu G 2004 Grain size effect on the electrochemical corrosion behavior of surface nanocrystallized low-carbon steel Corrosion 60 891–6
[10] Soleimani M, Mirzadeh H and Dehghanian C Processing route effects on the mechanical and corrosion properties of dual phase steel Met. Mater. Int. in press (https://doi.org/10.1007/s12540-019-00459-0)
[11] Mirzadeh H, Alibeyki M and Najafi M 2017 Unraveling the initial microstructural effects on mechanical properties and work-hardening capacity of dual phase steel Metalurgical and Materials Transactions A 48 4565–73
[12] Lei C, Chen X, Li Y, Chen Y and Yang B 2019 Enhanced corrosion resistance of SA106B low-carbon steel fabricated by rotationally accelerated shot peening Metals 9 872
[13] Cabrera J M, Ponce J and Prado J M 2003 Modeling thermomechanical processing of austenite J. Mater. Process. Technol. 143 403–9
[14] Diao G, Yan Q, Shi X, Zhang X, Wen Z and Jin X 2019 Improvement of wear resistance in ferrite–pearlite railway wheel steel via ferrite strengthening and cementite spheroidization Mater. Res. Express 6 106513
[15] Altamirano G, Mejia I, Hernandez-Expósito A and Cabrera J M 2012 Effect of boron on the continuous cooling transformation kinetics in a low carbon advanced ultra-high strength steel (A-UHSS) MRS Online Proceedings Library Archive 1485 83–8
[16] Soleimani M, Mirzadeh H and Dehghanian C 2019 Phase transformation mechanism and kinetics during step quenching of st37 low carbon steel Mater. Res. Express 6 11652
[17] Najafkhani F, Mirzadeh H and Zamanj M 2019 Effect of intercritical annealing conditions on grain growth kinetics of dual phase steel Met. Mater. Int. 25 1039–46
[18] Kumar S, Aashrith B, Samantaray D, Arvindh Davinci M, Borah U and Bhaduri A K 2018 Influence of nitrogen on kinetics of dynamic recrystallization in Fe–Cr–Ni–Mo steel Vacuum 156 20–9
[19] Lin Y C, Chen M S and Zhong Y 2008 Microstructural evolution in 42CrMo steel during compression at elevated temperatures Mater. Lett. 62 2132–5
[20] Dini G, Najafzadeh A, Ujei R and Monir-Vaghefi M 2010 Improved tensile properties of partially recrystallized submicron grained TWIP steel Mater. Lett. 64 15–8
[21] Mandal S, Ummadi R, Bose M, Balla V K and Roy M 2019 Fe–Mn–Cu alloy as biodegradable material with enhanced antimicrobial properties Mater. Lett. 237 323–7
[22] Lin Y C, Liu G, Chen M S, Zhang J L, Chen Z G, Jiang Y Q and Li J 2016 Corrosion resistance of a two-stage stress-aged Al–Cu–Mg alloy: Effects of external stress J. Alloys Compd. 661 221–30
[23] Shahali H, Ghaseemi H M and Abedini M 2019 Contributions of corrosion and erosion in the erosion-corrosion of Sanicro28 Mater. Chem. Phys. 233 366–77
[24] Lin Y C, Liu G, Chen M S, Huang Y C, Chen Z G, Ma X, Jiang Y Q and Li J 2016 Corrosion resistance of a two-stage stress-aged Al–Cu–Mg alloy: Effects of stress-aging temperature J. Alloys Compd. 657 855–65
[25] Eskandari F, Atapour M, Golozar M A, Sadeghi B and Cavaliere P 2019 Corrosion behavior of friction stir processed AISI 430 ferritic stainless steel Mater. Res. Express 6 086532
[26] Lin Y C, Zhang J L, Chen M S, Zhou Y and Ma X 2016 Electrochemical corrosion behaviors of a stress-aged Al–Zn–Mg–Cu alloy J. Mater. Res. 31 2493–305
[27] Soleimani M, Mirzadeh H and Dehghanian C Effects of tempering on the mechanical and corrosion properties of dual phase steel Materials Today Communications in press (https://doi.org/10.1016/j.mtcomm.2019.100745)

[28] Loto R T and Loto C A 2019 Evaluation of the localized corrosion resistance of 316 L austenitic and 430Ti ferritic stainless steel in aqueous chloride/sulphate media for application in petrochemical crude distillation units Mater. Res. Express 6 086516