Effect of hydrogen embrittlement and non-metallic inclusions on tensile fracture properties of 55CrSi spring steel

Na Li¹, Wei Wang¹² and Qimin Liang¹

¹ School of Materials Engineering, Shanghai University of Engineering Science, Shanghai 201620, People’s Republic of China
² Department of Nuclear Engineering and Radiological Science, University of Michigan, Ann Arbor, MI 48109-2104, United States of America

E-mail: wangwei200173@sina.com

Keywords: hydrogen embrittlement, non-metallic inclusion, fisheye, quasi-cleavage

Abstract

The tensile fracture behavior of 55CrSi spring steels were investigated. The results demonstrate that interior inclusion and hydrogen level has a significant effect on ductility and a minimal effect on tensile strength of the spring steel. It was due to the effect of cracking from MgO-Al₂O₃ spinel inclusion or the inclusions with a mixture of CaO, SiO₂ and part of Al₂O₃ due to hydrogen. The results of SEM showed that the ductility reduction is connected with the formation of ‘fisheye’ which formed under the influence of mobile hydrogen. For the specimen containing MgO-Al₂O₃ spinel inclusion, the fracture surface in the ‘fisheye’ area is mainly composed of three regions including typical quasi-cleavage mixed intergranular fracture, dimple mixed transgranular fractures and ductile fracture from the interior to the edge, whereas there is no obvious transition zone from brittle fracture to dimple fracture in the ‘fisheye’ area of the specimen containing inclusions with a mixture of CaO, SiO₂ and part of Al₂O₃.

1. Introduction

55CrSi is an alloyed spring steel used to produce quality springs for suspension, valve and coil products [1]. Due to the complex stress load during service, ductility and yield strength are required for the spring steel [2–4]. However, the ductility and yield strength are affected with the cleanliness to the spring steel [5–7]. The main factors to tensile failure are the local stress caused by nonmetallic inclusions, which contains the size, type and composition of inclusions, and difference in thermal coefficients of expansion between the steel and inclusions [8, 9]. Inclusions with poor deformability can induce cracks easily at the interfaces of the inclusions/steel matrix during hot rolling [10–12].

The major types of nonmetallic inclusions are oxides, sulfides and nitrides in the spring steel. In most cases, Al₂O₃, Al₂O₃–CaO or Al₂O₃–SiO₂–CaO–MgO, MnS, TiN or CaS inclusions will probably be present in commercial spring steel products [5, 13–15]. The entirely removal of such inclusions is often impossible due to ordinary manufacturing processes; it is desirable to control the kinds of nonmetallic inclusions and amount within trace limits that mechanism properties of the steel are nor relatively affected by nonmetallic inclusions.

As for the spring steel, the researches are focused mainly on increasing the strength and fatigue properties, and developing the ductility. In general, the susceptibility to hydrogen embrittlement increases with strength level increasing. It has been recognized that trace hydrogen in the steels may lead to hydrogen embrittlement [15]. Hydrogen embrittlement can reduce simultaneously strength, toughness and ductility of the steels. Alternatively, hydrogen embrittlement can also cause a significant reduction of ductility without decreasing in yield and tensile strength [16].

The solubility of hydrogen in the steels can be classified in two different categories. In generally, hydrogen in steel has a low solubility. However, hydrogen in traps has very high solubility [17]. There are two kinds of hydrogen traps in the steel. The first kind is weak traps. The binding energy between weak traps and hydrogen is smaller. Therefore, hydrogen can escape from the steel matrix. Another kind is strong traps. Internal inclusions

© 2020 The Author(s). Published by IOP Publishing Ltd
belong to strong traps. The binding energy between strong traps and hydrogen is higher. Hydrogen trapped by these strong traps can hardly escape from the steel matrix [6].

Lovciu et al [18] reported that nonmetallic inclusions has a greater contribution to hydrogen sensitivity in advanced high-strength steels. Studies show that the hydrogen cracking crack initiated at inclusions inside the tensile specimen [19, 20]. Furuya et al [21] proposed that hydrogen is segregated at voids which formed around inclusions. High concentration of hydrogen can induce voids growing and initiate cracking under tensile loading.

Different inclusion rating methods have been suggested. Cleanness of the steels can be remarkably improved by hydrogen embrittlement of a tensile test specimen than the methods by fatigue testing or optical microscopy [22].

Generally speaking, nonmetallic inclusions play the major role in hydrogen embrittlement, however, the interaction of nonmetallic inclusions and hydrogen is not yet clear in detail. The aim of this study is to further investigate the characterization of nonmetallic inclusions in spring steel based on a detailed microscope of the tensile fracture surfaces. Accordingly, clarify the effect of the type and composition of nonmetallic inclusion on hydrogen embrittlement of spring steels. The fundamental understanding of this question is essential to improve the final properties of the springs.

2. Experiments and materials

The investigated material is a high strength spring steel 55CrSi. The specimens were supplied by a steel company as wires. The chemical composition of the spring steel is given in table 1. The spring steel 55CrSi used here was hot-rolled wire rods. After acid pickling in 40 vol% NaCl for 10 min, phosphating and drying, the wire rods were ultrasonically cleaned in 99% alcohol for 30 min, then dried by the inert atmosphere. The sizes and composition of specimens were investigated using a scanning electron microscope (SEM) on a S3400-N instrument to identify the morphologies of the fractures. Samples for SEM were cut from the exposed core of the tensile test specimens and prepared by mechanical polishing and further ultrasonically cleaned in 99% alcohol for 30 min, then dried by the inert atmosphere. The sizes and composition of nonmetallic inclusions were measured using SEM and energy dispersive spectroscopy (EDS), respectively.

3. Results and discussion

3.1. Analysis of SEM microstructure

SEM micrographs in figures 1(a) and (b) show the microstructure of both the heat-treated specimens. Typical tempered martensitic structure (sorbite structure) can be seen in both specimens. As shown in figure 1, the microstructure of both the specimens consists of lath martensite with prior austenite grains, prior austenite grain boundaries are shown as the red dashed line in figures 1(a) and (b). The substructure consists of spherical cementite particles. From figure 1, it can obviously seen that there is no significant difference among both the specimens. It is known that prior austenite grain boundary and lath martensite is susceptible to hydrogen embrittlement because they can act as the path of crack propagation, and accelerate the rate of crack propagation [22, 23].

3.2. O, N and H contents of specimens Φ4.0 and Φ4.7 and mechanical properties

The H and O contents of specimens Φ4.0 and Φ4.7 are shown in table 2. It can be seen that the H and O contents of specimens Φ4.0 are 2.86 ± 0.239 ppm and 96.7 ± 4.88 ppm, and the H and O contents of specimens Φ4.7 are 6.19 ± 0.239 ppm and 161 ± 4.88 ppm, respectively.

The mechanical properties of specimens Φ4.0, Φ4.7 and normal specimens are shown in table 3. It can be seen that Φ4.0 and Φ4.7 specimens exhibit relatively high tensile strength, 1900 MPa for Φ4.0 specimen, and

| Table 1. Chemical composition of 55CrSi spring steel (wt%). |
|-----------------------------------------------------------|
| Elements | C  | Si | Cr | Mn | P   | S   | Cu |
|Composition | 0.55 | 1.5 | 0.7 | 0.7 | ≤0.03 | ≤0.03 | ≤0.2 |
1830 MPa for Φ4.7 specimen, respectively. However, the average values of elongation in specimens Φ4.0 and Φ4.7 are 27.6% and 20.7%, respectively. It is obvious that elongation of both the specimens is reduced, as compared to its normal specimen (40%). Meanwhile, tables 2 and 3 show the changes in strength and ductility of specimens Φ4.0 and Φ4.7 charged with various H contents. It is obvious that as hydrogen concentration increases, the tensile strength and ductility of the specimens decreases.

The content of oxygen really represents the level of oxide inclusions in the steel, so total oxygen is a very important and common index of steel cleanliness [24]. As shown in table 2, it can be seen that Φ4.0 and Φ4.7 specimens contain high content of oxygen. The excessive oxygen content resulted in the increase of inclusion quantity, which would deteriorate the cleanliness of the steel.

Based on the experimental data, it should be noted that hydrogen concentration and the impurity have a significant effect on ductility and a minimal effect on tensile strength of the spring steel.

The Vickers hardness obtained for Φ4.0 and Φ4.7 specimens are HV 563 and HV 537, respectively. The Vickers hardness has an important role in deciding the susceptibility to hydrogen embrittlement [25]. It is proposed that Vickers hardness of high strength steels is over HV400, hydrogen embrittlement occurs more markedly [21].

### 3.3. Analysis of SEM micrographs and composition of nonmetallic inclusions

Figure 2(a) shows the morphologies of the tensile fracture surfaces of the Φ4.0 specimen. A specific defect, known as ‘fisheye’ can be observed. The ‘fisheye’ is seen in SEM as elliptic shape. In a backscattered electron contrast, the ‘fisheye’ appears as bright areas, as shown in figure 2(b). Many researchers have reported that ‘fisheye’ was often found on the tensile fracture specimens after hydrogen pre-charging, and implying that the hydrogen atoms have diffused to the center of the cross-sectional area [26–28].

Two magnified images of the white spot in figure 2(a) and dark spot in figure 2(b) are shown in figures 2(c) and (d), respectively. Detailed views of a ‘fisheye’ region and of its counterpart on the matching side can be seen.
in figures 2(c) and (d), respectively. From the figure 2(c), it can be observed that a rectangular hole is surrounded by a mixture of ‘flat’ and ‘quasi-cleavage’ fracture features. On the fracture surface of counterpart, an inclusion is observed in the center of the internal ‘fish-eye’. The shape of inclusion is rectangular and the diagonal length is about 29 μm, as shown in figure 2(d). Meanwhile, figure 2(c) shows brittle fracture with four deep cracks. It is clear that these cracks originate at inclusions and propagate in a transgranular manner as evidenced by figure 2(d). The EDS of the inclusion analysis was carried out and the result is shown in figure 3. It reveals that the inclusion contains Al, Mg and O elements, designated as MgO-Al2O3 spinel inclusion.

Further observation shows that ‘fish-eye’ is mainly composed of three regions including crack initiation (region I), crack propagation (region II) and final fracture (region III), as shown in figure 4(a). Figure 4(b) presents some details of the fracture initiation region at higher resolution than figure 2(d). Details on fracture surface in the region I show a mixture feature of ‘flat’ and ‘quasi-cleavage’. Fine straight and Y-shaped tear ridges can be observed on the ‘flat’ region and ‘quasi-cleavage’ facets, as illustrated by arrows in figure 4(b). The magnified image of a white box ‘A’ in figure 4(a)
is shown in figure 4(c) which indicating the formation of serrated markings. It can be observed that the ‘quasi-cleavage’ fracture surface has lath microstructure within serrated markings, as shown by arrows in figure 4(c). In addition, figure 4(c) shows the secondary cracks (shown with the red dashed line), which propagate along prior austenite grain boundaries. It was reported [29–31] that secondary crack is closely related to hydrogen segregation along the prior austenite grain boundaries. These features basically indicate the occurrence of mixed fracture surface of intergranular and quasi-cleavage in the region I. The intergranular fracture is explained by the hydrogen-enhanced decohesion mechanism that dissolved hydrogen weakens the bonding of Fe lattice atoms [32]. Du proposed that a critical strain demanded for intergranular fracture is decreased due to hydrogen reduces the bonding of Fe atoms at grain boundaries [33].

The fracture surface outside of region I (region II) appears transgranular ductile fracture with tear ridges, as shown in the bottom right of figures 4(c) and (d). The region between region I and II exhibits the step change of roughness. This transition border is marked as dotted line in figure 4(c). As seen in figure 4(d), some voids are elongated which indicates ductile shear fracture has occurred in this region. Obvious shear and tear dimples together with a few equiaxed dimples are observed. These features basically indicate the occurrence of mixed fracture of ductile shear and transgranular fracture in the crack propagation region (region II).

The area outside of the crack propagation region (region III) corresponds to the final fracture surface. The high magnification image of a white box ‘B’ in figure 4(a) is shown in figure 5(a) which indicating the formation of waves on the region ‘B’, which demonstrates that ductile fracture occurred in the region ‘B’. The fractographic features indicate that fracture occurs through micro-void initiation and ductile tearing. It was suggested that micro-void initiation originates from very closely spaced nuclei, and that strain localization controls subsequent void growth [34].

Meanwhile, intergranular cracks along prior austenite grain boundaries can be seen on the fracture surface of the specimen, as shown by arrows ‘1’ and ‘2’ in figure 4(a). A vicinity of a crack (arrow ‘1’ region in figure 4(a)) is shown in figure 5(b). An enlarged image of the bottom right in figure 5(b) is shown in figure 5(c). Detailed observations near the arrow ‘1’ region reveal ductile fracture accompanied with a large number of dimples at the edges of intergranular cracks. Dimples in different size in ridges were also observed in figure 5(c). It indicates that a large number of ductile fracture occurred before complete rupture by localized shear.

Moreover, an enlarged image of region (A) in figure 2(a) is shown in figure 5(d). Detailed observations near region (A) outside of the ‘fisheye’ exhibit dimple fracture. The region outside of the ‘fisheye’ corresponds to the final fast fracture surface.

Figure 4. The detail microstructure and morphology of the tensile fracture for the Φ4.0 specimen. (a) Microscopic morphology of circular pits and fibers; (b) enlarged view of figure 2(c); (c) magnified image of ‘A’ area in figure 4(a); (d) magnified image of ‘C’ area in figure 4(c).
From the above results, it can be concluded that, for the specimen containing MgO–Al₂O₃ spinel inclusion, the fracture surface in the ‘fisheye’ area is mainly composed of three regions including typical quasi-cleavage mixed intergranular fracture (region near the crack origin), dimple mixed transgranular fractures and ductile fracture from the interior to the edge. The difference among three fracture features could be attributed to hydrogen content at the near tip of cracks, the stress condition and the rate of crack growth \[35\]. During the period for the crack initiation, the specimen is in a approximately plane-strain condition, the hydrogen content is higher due to concentration of stress at the near tip of cracks, brittle quasi-cleavage fracture would like to induce in the combined effect of hydrogen atom and stress condition. During the period for the crack propagating, the specimen can nearly be regarded as the state of plane stress. Moreover, because of the rate of the crack propagation is higher than that of the crack initiation, hydrogen content at the near tip of cracks decreases due to hydrogen atom transfer, so ductile fracture prefers to occur in this condition \[35\].

Figure 6(a) shows the morphologies of the tensile fracture surfaces of the Φ4.7 specimen. ‘Fisheye’ is also be observed on the fracture surfaces of the Φ4.7 specimen. The ‘fisheye’ is seen in SEM as elliptic shape. Two high magnification images of the central region in figure 6(a) are shown in figures 6(b) and (c). Detailed views of a ‘fisheye’ area and of its counterpart on the matching side can be seen in figures 6(b) and (c). In the figure 6(b), a similar circular hole with a mixture of ‘flat’ and ‘quasi-cleavage’ fracture features is seen. On the counterpart, an inclusion is observed in the center of the internal ‘fisheye’, as shown in figure 6(c). The shape of inclusion is spherical and the diameter of inclusion is about 60 μm.

The magnified image around the inclusion in figure 6(c) is shown in figure 6(d) indicating the formation of serrated markings. It can be seen that the secondary cracks (shown with the red dashed line), which propagate along prior austenite grain boundaries. Clearly, the secondary cracks in the Φ4.0 specimen are short and blunt, while those in the Φ4.7 specimen are relatively deep and sharp. In addition, a high magnification image of a white box ‘A’ in figure 5(a) is shown in figure 7(a), some distinct embrittled cracks are revealed. An enlarged image of the left in figure 7(a) is shown in figure 7(b). Detailed observations reveal a clearly distinguishable embrittled edge along the fracture surface (figure 7(a)), while the periphery of cracks was rather ductile with numerous large and shallow dimples (figure 7(b)). It should be noted that there is no obvious transition zone from brittle fracture to dimple fracture in the ‘fisheye’ area of the Φ4.7 specimen in comparison with that of the Φ4.0 specimen.
It can be obviously seen from figure 6(c) that the interfaces between the inclusion and the matrix are not cohesive. In comparison with the Φ4.0 specimen, the interface cohesive of the Φ4.7 specimen is the worst. Moreover, the EDS result in figure 8 shows that the inclusion contains of O, Ca, Si and Al elements. It can be concluded that the inclusion was mainly composed of CaO, SiO₂ and part of Al₂O₃.

3.4. Summary
In present study, two specimens have same compositions and heat treatment processing. It is obvious that tensile strength and elongation of both the specimens are reduced, as compared to its normal specimen. However, compared with Φ4.7 specimen, the Φ4.0 specimen exhibit higher tensile strength because of cohesive MgO–Al₂O₃ spinel inclusion. Two specimens have different sizes (Φ4.0 mm and Φ4.7 mm), but, there is least
size difference between the two specimens, thus, under the assumption that the influence of specimen size on mechanical properties and fracture behavior may be neglected.

Various kinds of inclusions is a result of the varying mechanism properties of the specimens. For the inclusion with a mixture of CaO, SiO2 and part of Al2O3, the fracture surface of the specimen showed an evident gap at the inclusion/matrix interfaces, as shown in figure 6(c). During the tensile test, the degree of deformation between the inclusion and matrix is different. It is inevitable that the concentration of stress at the inclusion/matrix interfaces will be induced, which results in the aggregation of hydrogen at the inclusion/matrix interfaces due to hydrogen atoms diffusion driven by the stress gradient-induced. Once hydrogen content exceeds the critical value for crack initiation, hydrogen induced cracking occurs immediately. Inclusion with MgO-Al2O3 spinel inclusion which has a sharp shape and are tightly bound to the matrix, as shown in figure 2(d). The cohesive interfaces between the inclusion and matrix may lead to a lower concentration of stress and reduce the possibility of crack initiation.

Compared with the ∅4.0 specimen, the inclusion within the ∅4.7 specimen has an evidently larger size. Furthermore, it is known that the smaller inclusion may lead to a lower concentration of stress and reduce the possibility of crack initiation [36]. Furthermore, the secondary cracks that initiated from the prior austenite grain boundaries, as indicated in figures 2(c) and 6(d), it further demonstrates a significant aggregation of hydrogen atoms in the prior austenite grain boundaries. Thus, it can be inferred that hydrogen embrittlement plays an important role in accelerating the initiation and growth of the secondary cracks.

4. Conclusions

In this study, the effect of hydrogen on the tensile strength of 55CrSi spring steels and fracture behavior were investigated. Based on the experimental results and the analysis, the conclusions are drawn as follows:

(1) The tensile strength and elongation of 55CrSi spring steel are reduced due to the combined effect of nonmetallic inclusion and hydrogen.

(2) Inclusion with MgO-Al2O3 spinel nonmetallic inclusion which has a sharp shape and are tightly bound to the matrix. For the inclusion with a mixture of CaO, SiO2 and part of Al2O3, the fracture surface of the specimen showed an evident gap at the inclusion/matrix interfaces.

(3) For the specimen containing MgO–Al2O3 spinel inclusion, the fracture surface in the ‘fisheye’ area is mainly composed of three regions including typical quasi-cleavage mixed intergranular fracture, dimple mixed transgranular fractures and ductile fracture from the interior to the edge, whereas there is no obvious transition zone from brittle fracture to dimple fracture in the ‘fisheye’ area of the specimen containing inclusions with a mixture of CaO, SiO2 and part of Al2O3.

Acknowledgments

The authors would like to thank Mr. Chang (Xuhua Chang, Sinosteel Zhengzhou Research Institute of Steel Wire Products Co., Ltd.) for supplying the samples. The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (No. 51271111).
References

[1] Hu Y, Chen W, Wan C and Wang F 2018 Effect of deoxidation process on inclusion and fatigue performance of steel for automobile suspension Metallurgical and Materials Transactions A 49B 569–80

[2] Zurnadzhi V I, Efremenko V G, Wu K M, Azarkhov A Y, Chabuk Y G, Greshita V L, Isayev O B and Pomazkov M V 2019 Effects of stress relief tempering on microstructure and tensile/impact behavior of quenched and partitioned commercial spring steel Materials Science and Engineering A 745 307–18

[3] Yang Z G, Li S X, Li Y D, Liu Y B, Hui W I and Weng Y Q 2010 Relationship among fatigue life, inclusion size and hydrogen concentration for high-strength steel in the VHCF regime Materials Science and Engineering A 527 559–64

[4] Jiang Y, Liang Y L, Yin C H, Long S L, Zhao F and Xiao Y 2018 Influence of multiphase on the strain hardening behavior of 60Si2CrVAT spring steel treated by a Q–P–T process J. Mater. Sci. 53 10396–410

[5] Bytyqi A, Jenko M and Godec M 2012 Analysis of inclusions in spring steel using scanning electron microscopy and Auger spectroscopy Vacuum 86 648–51

[6] Li Y D, Yang Z G, Liu Y B, Li S X, Li G Y, Hui W I and Weng Y Q 2008 The influence of hydrogen on very high cycle fatigue properties of high strength spring steel Materials Science and Engineering A 489 373–9

[7] Karr U, Schönauer B, Fitzka M, Tamura E, Sandiaji Y, Murakami S and Mayer H 2019 Inclusion initiated fracture under cyclic torsion very high cycle fatigue at different load ratios Int. J. Fatigue 122 199–207

[8] Thornton P A 1971 The influence of nonmetallic inclusions on the mechanical properties of steel: a review J. Mater. Sci. 6 347–56

[9] Lankford J 1977 Effect of oxide inclusions on fatigue failure Int. Mater. Rev. 22 221–8

[10] Atkinson H V and Shi G 2003 Characterization of inclusions in clean steels: a review including the statistics of extremes methods Prog. Mater. Sci. 48 457–520

[11] Murakami Y and Endo M 1994 Effects of inclusions and inhomogeneities on fatigue strength Int. J. Fatigue 16 163–82

[12] Gustavsson A I and Melander A 1992 Fatigue limit model for hardened steels Fatigue Fract. Eng. Mater. Struct. 15 881–94

[13] Furuya Y, Matsuoka S and Abe T 2004 Inclusion-controlled fatigue properties of 1800 MPA-class spring steels Metallurgical and Materials Transactions A 35A 3737–44

[14] Shi W, Yang S, Dong A and Li J 2018 Understanding the corrosion mechanism of spring steel induced by MnS inclusions with different sizes JOM 70 2513–22

[15] Dwivedi S K and Vishwakarma M 2018 Hydrogen embrittlement in different materials: a review Int. J. Hydrogen Energy 43 21603–16

[16] Venezuella J, Zhou Q, Liu Q, Li H, Zhang M, Dargusch M S and Atrens A 2018 The influence of microstructure on the hydrogen embrittlement susceptibility of martensitic advanced high strength steels Materials Today Communications 17 1–14

[17] Chapetti M D, Itagawa T and Miyata T 2012 Ultra-long cycle fatigue of high-strength carbon steel Rev. and analysis of the mechanism of failure Materials Science and Engineering A 507S 87–97

[18] Lovicu G, Bottazzi M, D’auto F, De Sanctis M, Dimatteo A, Santus C and Valentini R 2003 Hydrogen embrittlement of automotive advanced high-strength steels Materials Science and Engineering A 356 227–35

[19] Han G and Feng D 1995 Effects of hydrogen on behaviour of low cycle fatigue of 2.25Cr-1Mo steel J. Mater. Sci. Technol. 11 353–7

[20] Tsuchida Y, Watanabe T, Kato T and Seto T 2010 Effect of hydrogen absorption on strain-induced low-cycle fatigue of low carbon steel Procedia Engineering 2 553–61

[21] Fujita S and Murakami Y 2013 A new nonmetallic inclusion rating method by positive use of hydrogen embrittlement phenomenon Metallurgical and Materials Transactions A 44A 303–22

[22] Thomas R L S, Scully J R and Gangloff P R 2003 Internal hydrogen embrittlement of ultrahigh-strength AERMET 100 steel Metallurgical and Materials Transactions A 34 327–44

[23] Nagao A, Smith C D, Dadfarinia M, Sofronis P and Robertson I M 2012 The role of hydrogen in hydrogen embrittlement fracture of lath martensitic steel Acta Mater. 60 5182–9

[24] Zhang L F and Thomas B G 2003 State of the art in evaluation and control of steel cleanliness ISIJ Int. 43 271–91

[25] Das T, Rajagopalan S K, Brahimis S V, Wang X and Yue S 2018 A study on the susceptibility of high strength tempered martensite steels to hydrogen embrittlement (HE) based on incremental step load (ISL) testing methodology Materials Science and Engineering A 716 189–207

[26] Santofimia M J, Zhao L and Sietsma J 2009 Microstructural evolution of a low-carbon steel during application of quenching and partitioning heat treatments after partial austenitization Metallurgical and Materials Transactions A 40 46–57

[27] Li H X, Venezuela Jeffrey, Zhou Q J et al 2020 Effect of plastic strain damage on the hydrogen embrittlement of a dual-phase (DP) and a quenching and partitioning (Q&P) advanced high-strength steel Materials Science and Engineering A 785 139343

[28] Yang J, Song Y, Lu Y, Gu J and Guo Z 2018 Effect of ferrite on the hydrogen embrittlement in quenched-partitioned tempered low carbon steel Materials Science and Engineering A 712 630–6

[29] Araujo M A and Szpunar J A 2011 Effect of bainitic microstructure on the susceptibility of pipeline steels to hydrogen induced cracking Materials Science and Engineering A 528 927–40

[30] Venezuella J, Liu Q, Zhang M, Zhou Q and Atrens A 2015 The influence of hydrogen on the mechanical and fracture properties of some martensitic advanced high strength steels studied using the linearly increasing stress test Corros. Sci. 99 98–117

[31] Nanninga N E, Levy Y S, Drexl E S, Condon R T, Stevenson E A and Slika J A 2012 Comparison of hydrogen embrittlement in three pipeline steels in high pressure gaseous hydrogen environments Corros. Sci. 59 1–9

[32] Han J, Nam J and Lee Y 2016 The mechanism of hydrogen embrittlement in intercritically annealed medium Mn TRIP steel Acta Mater. 113 1–10

[33] Du Y A, Ismer L, Rogal J, Hickel T, Neugebauer J and Drautz R 2011 First-principles study on the interaction of H with grain boundaries in α- and γ-Fe Phys. Rev. B 84 144121

[34] Williams J J, Piotrowski G, Saha R and Chawla N 2002 Effect of overaging and particle size on tensile deformation and fracture of particle-reinforced aluminum matrix composites Metallurgical and Materials Transactions A 33 3861–9

[35] Oriani R A 1978 Hydrogen embrittlement of steels Annu. Rev. Mater. Sci. 8 327–57

[36] Shen S, Song X, Li Q, Li X, Zhu R and Yang G 2019 A study on stress corrosion cracking and hydrogen embrittlement of martensitic stainless steel Materials Science and Engineering A 740–741 243–51

---