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A review: The impact of hydrogen embrittlement on the fatigue strength of high strength steel

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A B S T R A C T

The purpose of this paper is to investigate the change in fatigue crack growth behavior resulting due to hydrogen embrittlement in different steels like low carbon steel, advance high strength steel, Cr- Mo and stainless steel but main focus is given on advance high strength steels. These AHSS are mostly found in the automobile sector because of its excellent properties. And hydrogen embrittlement is a phenomenon that is affecting it in the ways that it initiates crack enlargement in metal, fracture initiation and failures causing deterioration of mechanical properties. SEM and TEM have been used to study the impacts.

Selection and of the scientific committee of the 10th International Conference of Materials Processing and Characterization.

1. Introduction

Hydrogen embrittlement is a phenomenon that makes steel brittle where hydrogen gases can get trapped on the interior of the liquid metal during the solidification process and penetrate the interior of the base material causing the generation of crack. This causes properties (like tensile strength and fatigue strength) of steel to deteriorate [6]. Hydrogen in an industry can enter by processes like electroplating, cathodic charging, and welding. Due to hydrogen embrittlement mainly two types of fracture occurred on the interior of the metal they are intergranular fracture and transgranular fracture. Intergranular fracture is one type of brittle fracture, the cracks propagate through the material at high speed, whereas in trans granular the fractures occurred outside the grain boundaries [14]. Here the extension of fractures shows how the properties of a material have been affected due to hydrogen embrittlement, which makes it very imp to study the fracture growth mechanisms. In most cases, hydrogen has been known to lower the strength and the ductility of the metal. While in fatigue failure cases the lower the loading frequency the more time hydrogen will get to enter the metal and more severely it will affect it [12]. Different types of testing have been done for checking the strength and properties of the material for example fatigue testing and tensile testing are preferred. Fatigue strength tests are another way to determine material property as it tells cyclic fatigue loading conditions of the material. It also tells the maximum amount of load a material can withstand. The crack growth rate increases as load frequency decrease from 1.5 Hz to 0.0015 Hz [11]. Another method of testing is universal testing machines, and it especially measures characteristics of tensile strength, yield strength, elongation and modulus of elasticity. The fatigue life of material is mainly dependent on pressure, temperature and microstructure of a material, fatigue life of high strength steel is far better compared to other material. Subcritical crack growth is also responsible for fatigue crack initiation, Due to dislocation and misalignment of the grain boundaries defect is generated due to this defect crack is generated. Subcritical cracks say a lot about what stress or what material the base metal is made up of. It starts with the crack tip and these cracks are self-limiting but will only progress only if the stress increases. Subcritical crack growth is mainly dependent on the properties and loading conditions of the material. Stress intensity factor (k) is used to determine the state of stress near subcritical stress. For crack growth threshold stress should be below the yield stress. The size of crack at which it becomes unstable is called critical crack size and fatigue failure becomes rapid when it reaches critical crack [21,44]. The material which is affected due to hydrogen embrittlement is high strength steel, advanced high strength steel, high Mn steel, Aluminum alloys, carbon- steels, etc, mostly in current scenario high strength steel is most widely used because whose strength (1000 Mpa) and mechanical properties are better and used in many industries [7,32,41,42].

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2. Literature survey

Investigations (by G.Gabetta et al) show that engineer required simple and effective approach during material selection in design and manufacturing stage, to reduce the failure of the specimen during an operating period and sometimes increases the operational life & the strength of the material. The transition between two zones crack nucleation and crack propagation and the impact of surface hardness in sample/component cracking can be studied using fracture mechanics [1].

Next paper (Jeffrey venzuela et al) studies the impacts of HE on Advance high strength steels. This alloy steel because of its high ductility, formability and resistance to corrosion are used in the automobile sector. Here Martensitic advanced high strength steel is said to be the strongest among all other types. Strengthening of it is done by grain refinement, phase transformation and cold deformation etc. Hydrogen charging conditions and hydrogen concentration with hydrogen embrittlement in Ms-AHSS are not clear. Hydrogen concentration has a big role to play in the type and volume of hydrogen embrittlement and this clustering of hydrogen is determined by aspects like mechanical strength, residual stress and process [2].

Another investigation (by Le Li et al) on the impacts of corrosion by submersing the steel into the HCl solution was done. This paper shows that mechanical properties are adversely affected by corrosion, where it is the simultaneous impacts of grain size, phase composition and residual stresses. It was also found that there is a significant loss in ultimate strength, yield strength and ductility of the steel due to corrosion [3].

The next paper (by Yu Matsumoto et al) shows that hydrogen desorption increased during cyclic stress testing and elastic stages of constant stress/strain. Hydrogen desorption behavior required a different type of testing mainly cyclic stress testing and constant stress testing use. For testing the specimen mainly AHSS is taken because it has better mechanical strength and greater resistance to corrosion. Hydrogen desorption behavior is different for different testing, in tensile testing hydrogen desorption is maximum near the yield points, in constant stress testing the hydrogen desorption behavior is increase where nominal stress is started and then it gradually decreases, in cyclic stress testing the hydrogen desorption is constant [4].

An investigation by M.B djukic et al showed that the impacts of hydrogen embrittlement at high temperatures, they found that hydrogen atom diffuses into the metal and developed crack and corrosion. For checking the hardness and strength of specimen Charpy testing and SEM were used. In this paper it was investigated that hydrogen embrittlement is a simultaneous effect of HELP and HEDE, this simultaneous effect is responsible for reduces the ductility [5].

H Barthelemy et al stated that the phenomenon of HE occurs because of entry of atomic hydrogen. The embrittlement of steel depends on several aspects such as environments, material of the metal and surface state. For understanding hydrogen embrittlement in the high-pressure hydrogen storage tank effective testing method done during operating conditions like tensile testing, fracture mechanics test and compact test used [6].

Paper by Dwivedi & Vishwakarma says a lot about the degradation of properties because of hydrogen embrittlement. It also causes fracture initiation causing loss of mechanical properties (for example ductility, toughness and strength, etc). Many mechanisms were studied by the author and they found that HELP and HEDE mechanisms were the most prominent ones causing damage. Hydrogen embrittlement occurs mainly in HSS, high Mn steel, and some AHSS. They also suggested ways to reduce the same by the addition of alloys like Al &Titanium [7].

Xinfing Li et al studied the impacts of pre-strain on hydrogen embrittlement on steel (mainly HSS) and used SSRT testing to determine the impacts. It was observed that as the amount of pre-strain increases the amount of hydrogen in metal increases I.e. it is directly proportional. While when they saw the impacts of hydrogen embrittlement first it decreased with an increase in pre-strain and later when it was further increased, hydrogen embrittlement increased. Fracture mode examination showed a mixed-mode of quasi-cleavage as well as Intergranular type fracture after it was hydrogen charged [8].

In one of the investigations by T. Depover et al, found thathydrogen embrittlement deteriorates mechanical properties of HSS employing tensile test of notch sample, mechanical test was performed on both specimens hydrogen charged and hydrogen uncharged specimen, it was found that due to hydrogen charging the specimen structure changes from ductile to trans granular. To study the impacts of HE, four alloy steels were tested and an uncharged specimen showed a ductile fracture near the neck and a charged specimen showed brittle transgranular fractures near the edges [9].

J. Sanchezb in their paper stated that hydrogen embrittlement hydrogen was generated on high strength steel by using fixed cathodic potential and high temperature therefore crack initiation has occurred. The high strength steel was dipped in a saturated 0.1 M Nacl solution simultaneously the high strength steel was applied to tensile load at slow strain rate until fracture. When the applied load was above the yield stress then quasi-cleavage type fracture occurred. This paper discussed the utility of HE of HSS in different chloride contaminated solution, under the cathodic condition and different stress condition, Fractographic analysis was done. They found that dimple microvoidshave occurred at the center and the edge of the high strength steel produces ductile fracture [10].

In the review paper by A Roy et al they reviewed that at low-stress intensity factors hydrogen damage was seen to be quite high. According to the paper, crack growth rate and driving force are directly proportional to each other. The two important parameters which are discussed in the mentioned paper hydrogen enhanced fatigue and fatigue crack growth rate are inversely proportional to each other [11].

The investigations of Ali Rajabipour et al state that hydrogen embrittlement reduces ductility and mechanical properties such as strength, further leading to an increase in fatigue cracks. This type of cracking can be classified int two main types, I.e. Hydrogen enhanced decohesion (HEDE) (is also called 'traction separation law') and another on is Hydrogen enhanced localized plasticity (HELP). The methodologyis used for predicting the service life of corrosion pitted pipes [12].

Another paper by Seok weon song et al investigated that increasing carbon content assists an increasing number of monotonic tensile deformation. The present study stated that increasing carbon content greatly affected the tensile properties, microstructure, yield stress, ultimate tensile stress and total elongation of the specimen, increasing carbon content also decreases the fatigue life of the specimen [13].

Investigations by Jeffrey Venezuela et al says that when a large number of hydrogen atoms diffuse in metal then fracture initiation takes place, fracture initiation occurs. MS AHSS is a novel class of high strength steel that is presently used in the automotive body and power plant industry. MS-AHSS have less ductility and formability as compare to other types of advanced high strength steel. MS-AHSS is just similar to other high strength steel, it is unprotectable to hydrogen embrittlement. This paper studies how HE has affected and in what ways it enters the MS AHSS material. After the fractographic study, three main types of structure were seen I.e. transgranular, Intergranular and quasi cleavage type [14].

Investigation of fatigue cracks by L Briottet et al says that fatigue crack initiation and fatigue crack growth occur at room temperature and in a hydrogen pressure condition of 0.5-35Mpa. Here the low alloy steel was quenched and when the loading conditions are constant, fatigue crack growth depends on loading frequency and stress intensity factor [15].

The review by Motomichi Koyama et al tellsthat high strength material has excellent strength and higher ductility. The chemical composition of various alloying elements simultaneously affected the phase stability, behavior of hydrogen atom and stacking fault energy of materials. Due to hydrogen interaction between localized slip and misalignment of grain boundaries in material quasi cleavage type of fracture occurred in the material, quasi cleavage fracture decreases the strength and ductility. The hydrogen embrittlement greatly affected the high strength material, for improving the resistance of hydrogen embrittlement different types of alloying mixing like Al, Mn, and grain refinement are required [16].

The review paper by T.Doshida et al found that there was a presence of lattice defect while cyclic loading was applied (this was even without the presence of hydrogen). But when a tensile test was done on a hydrogen charged sample, it did not show any recognizable side impacts on it [17].

T.c Chen et al investigated the consequence of stress ratio on the fatigue crack's growth rate of high strength steel in hydrogen concentration. The fatigue crack growth rate is increased with increasing stress intensity factor and higher stress ratio. In MSAHSS the α-martensite layer was responsible for the fatigue crack growth of the sample. SEM is used to check the microstructure and fracture analysis of the material [18].

P. Fassina et al investigated that the consequence of hydrogen and temperature on fatigue crack growth of materials. The fatigue test was done to check the mechanical strength of hydrogen charged and hydrogen uncharged specimen. Frequency, temperature and load frequency are a more important parameter for finding the crack growth rate in materials. From fatigue testing, they found that the crack growth rate increases very sharply for hydrogen charged specimens [19].

Yukitaka Murakami et al investigated the consequence of hydrogen on the the crack growth rate on HSS. The hydrogen effect causes due to localization of slip, softening, hardening and creep. For satisfactorily and reliable service for up to 15 years, there is basic and reliable data on the fatigue behaviour of materials required in a hydrogen climate. Mainly there is two fuel cell system used in the current scenario [20].

Stationary fuel cell (2) automotive fuel cell system. In the fuel cell vehicle components like a high-pressure storage tank, valve pressure sensor and hydrogen accumulators were exposed in a hydrogen climate for approx. 15 years. In this paper, it was found that the fatigue cracks growth rate increases with a decrease in loading frequency.

3. Literature summary

Table 1.

4. Mechanism responsible for hydrogen embrittlement

Various mechanisms are responsible for hydrogen embrittlement such as HEDE, HELP, AIDE, and most of the time a brew of these is cause for deterioration and embrittlement [26].

4.1. Hydrogen enhanced decohesion mechanism (HEDE)

This is earliest model conferred the change of properties of the material as a result of atomic hydrogen. HEDE was characterized first in 1941 by Zaffe& sims. When hydrogen solubility is more in materials then hydrogen atom is diffused rapidly on interior of the material and it decreases the interatomic strength of the material at the crack tip and it formed cleavage type of fracture [26,28–30].

4.2. Hydrogen enhanced localized plasticity (HELP)

This was represented in 1972 and it is most widely used. In this, the hydrogen atom is accrued near the crack tip. It also reduces the resistance to dislocation motion. Therefore, the maneuverability of dislocation increases and dislocation performs as a bearer of plastic deformation in a metal lattice. It may evident that it relies upon the hydrogen clustering or microstructure or stress intensity aspects of the material. For checking the microstructure properties of material fractographic analysis was done. HELP contains numerous structures such as FCC, BCC and HCP type structure [27,31–34].

4.3. Adsorption induced dislocation emission (AIDE)

This is the consolidation of both, HEDE and HELP. The solute hydrogen atoms get adsorbed adjacent to crack tip. Adsorption of hydrogen at crack tip cripples the interatomic bonds and cohesive strength of materials by the HEDE mechanism, due to solute hydrogen atom dislocation formed near the crack tip. Dislocation facilitates the crack growth by slip and generation of microvoids by the HELP mechanism [35–37].

4.4. Mixed fracture

Mixed fracture is the combined effect of both ductile and brittle material. This type of fracture mechanism is known as the mixed fracture mechanism, in which case both the fracture modes are involved with each other [31,38].

5. Hydrogen charging

Naturally to show effect hydrogen embrittlement can take years and it will be very difficult to investigate it. So we use hydrogen embrittlement to enter hydrogen into metal. In the first paper the author studied the effect of HE in AISI 304 K-TIG with dimension 300 mm $\times$ 150 mm $\times$ 8 mm and was used as cathode while platinum net was used as anode. H2SO4 and NH4SCN were used as solution with different current densities. Here the hydrogen quantity was found to be 0.001 WPPM [22].

Next Author who studied 310S stainless steels (in the shape of rod) charging and used sulfuric acid and thiourea as solution. Again in the same way the specimen was used as cathode and charged for 48 h in current density of 2590 A/m2. Which showed reduction in fatigue strength after testing [23].With studying different cases it is clear that higher the current density, higher is the entry of hydrogen [24,39,40].Many experimentalists tried a new method like three electrode method and found it very precise [25].

6. Factor affecting the hydrogen embrittlement

Many factors cause HE in metals for example

6.1. Environment

Climate factor affecting the hydrogen atom into the high strength steel was scrutinized by hydrogen permeation test under cyclic loading showing that it had detrimental effects.

Table 1
Table of literature summary.

Sr. No.	Author and year	Title	Observation
1	G.Gabetta, P.Cioffi, Et al (2018)	Engineering thought on Hydrogen Embrittlement	HE is caused by a combination of stress, pressure and the surrounding climate (H2S or CO2) along with temperature, Ph or microstructure of metal.
2	Jeffrey Venezuela, QinglongLiu, Et al (2016)	A review of hydrogen embrittlement of martensitic advanced high-strength steels	MS- AHSS is the strongest among all the classes of steel. The strengthening mechanism for AHSS is grain refinement, phase transformation, and cold deformation, etc. many techniques are used to boost the toughness of MS-AHSS. The clustering of hydrogen and contamination can also be lessened to avoid the severity of HE.
3	Le Li, Mojtaba, Mahmoodian, Et al. (2018)	Effect of corrosion and hydrogen embrittlement on microstructure and mechanical properties of mild steel	Corrosion tests say that properties of material reduced after they corroded and these were dependent on aspects like a simultaneous consequence of grain size as well as phase composition and residual stresses.
4	Yu Matsumoto, Tomonori Miyashita, Et al. (2018)	Hydrogen behavior in high strength steels during various stress applications corresponding to different hydrogen embrittlement testing methods	In constant stress testing the hydrogen desorption behavior increases, while in nominal stress conditions it decreases and in cyclic stress testing the hydrogen desorption is constant.
5	M.B djukic et al (2014)	Hydrogen embrittlement of low carbon structural steel	Here we get to understand how hydrogen atom can enter the specimen and combine to for bigger molecules while increasing pressure inside causing crack.
6	H Barthelemy (2010)	Effects of pressure and purity on the hydrogen embrittlement of steels	The consequence of high pressure and high purity H2 was seen on metals. As the pressure increased, HE increased but also depend on the material. Austenitic steels were the safest option for the same.
7	Sandeep Kumar Dwivedi, Manish Vishwakarma (2018)	Hydrogen embrittlement in different materials: A review	It is very important to know the behavior of crack growth and the rate at which it proceeds in material, for reducing the hydrogen embrittlement phenomena selection of material is more important and also adding of some alloy like (Al &Titanium) hydrogen embrittlement is seen to be reduced.
8	Xinfeng Li, Yanfei Wang, Et al. (2014)	Effect of pre-strain on hydrogen embrittlement of high strength steels	The amount of pre-strain increases amount of hydrogen in metal increases I.e. it is directly proportional. While when they saw the consequence of hydrogen embrittlement first it decreased with an increase in pre-strain and later when it was further increased, hydrogen embrittlement increased.
9	T.Depover, D. Perez Escobar Et al. (2014)	Effect of hydrogen charging on the mechanical properties of advanced high strength steels	Ductility loss of four HSS steel, where TRIP steel had HE of 60% and DB and HSLA showed 8% HE.Showing that there is some relation between strength and HE of steel.
10	J. Sanchez, S.F. LeeEt al. (2015)	Measurement of hydrogen and embrittlement of high strength steels	The paper says that the entry of hydrogen will only occur in an iron sample if it is subjected to some stress or tension which should be above the elastic limit.
11	A. Roy, I. Manna, I. Chattoraj (2013)	Anomalies in hydrogen enhanced fatigue of a high strength steel	The study of fatigue crack growth shows that it increases with a decrease in stress intensity factor and increases with an increase in exposure time.
12	Ali Rajabipour, Robert E. Melchers (2018)	The service life of corrosion pitted pipes subject to fatigue loading and hydrogen embrittlement	The cracks in the pipe wall were studied and showed that under normal circumstances the pressure changes will not cause failure while the pipe is affected by; HE it will not be able to take the pressure for a long time and crack.
13	Seok Weon Song, Jae-Nam Kim Et al. (2018)	Effects of carbon content on the tensile and fatigue properties in hydrogen charged Fe-17Mn-xC steels	HE increased when carbon content increased. Two systems I.e. twinning and slipping. While twinning provided hydrogen enriches sites, the wavy slips were found and dispersion of hydrogen occurred.
14	Jeffrey Venezuela,c, Et al. (2018)	The influence of microstructure on the hydrogen embrittlement susceptibility of martensitic advanced high strength steels	Martensite has a brittle nature and thus it is less tolerant of embrittlement. But due to its properties, it traps hydrogen and causing cracks.
15	L. Briottet, I. Moro, Et al. (2015)	Fatigue crack initiation and growth in CrMo steel under hydrogen pressure.	When constant load ratio is applied, the after-effect of hydrogen on fatigue crack growth depends on aspects like loading frequency and stress intensity factor.
16	Motomichi Koyama, Eiji Akiyama, Et al. (2017)	Overview of hydrogen embrittlement in high-Mn steels.	High-Mn austenitic steels have found to be very resistant to HE. Similarly, Al addition to Austenitic stainless steel has also shown resistance to HE. Another method is Grain refinement.
17	T. Doshida , M. Nakamura Et al. (2013)	Hydrogen-enhanced lattice defect formation and hydrogen embrittlement of cyclically prestressed tempered martensitic steel.	When the specimen was provided with cyclic stress without Hydrogen charge the crack growth was lesser than in a Hydrogen charged sample.
18	T.C. Chen, S.T. Chen, W. Kai, L.W. Tsay (2015)	The effect of phase transformation in the plastic zone on the hydrogen assisted fatigue crack growth of 301 stainless steel.	The fatigue cracks growth rate increases with an increase in stress intensity factor and higher stress ratio. In MS-AHSS, the α-martensite layer is responsible for the fatigue crack growth rate of sample.
19	P. Fassina, M.F. Brunella Et al. (2012)	Effect of hydrogen and low temperature on fatigue crack growth of pipeline steels.	The fatigue test was done to check the mechanical strength of hydrogen charged and hydrogen uncharged specimen. From fatigue testing, they found that the crack growth rate increases very sharply for hydrogen charged specimens.
20	Yukitaka Murakami, Saburo Matsuoka (2010)	Effect of hydrogen on fatigue crack growth of metals	The hydrogen effect is caused due to the localization of slip, softening, hardening and creep.

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6.2. Applied load

For checking the hydrogen embrittlement in material load can be both static and dynamic. Types of fractures will also different for different loading conditions like - corrosion fatigue, stress corrosion fatigue, etc.

6.3. Material susceptibility

For reducing the hydrogen embrittlement the material is made of high strength steel, high strength alloy. In the current scenario for checking the susceptibility of material different type of testing were done [27,43].

7. Conclusion

The basic working of HE is to reduce the ductility of material and making it brittle. The hydrogen embrittlement is the cause for the degradation of mechanical properties. In this review paper, we introduced the causes and workings of hydrogen embrittlement. The diffusion of hydrogen is responsible for crack enlargement in materials. The crack growth rate is mainly dependent on stress intensity factor and loading frequency, with decreasing loading frequency the chances of fatigue crack growth rate of specimen will increase. This paper has been also discussed that microstructure and type of loading condition greatly affected the HE susceptibility of high strength steel. To reduce the HE selection of material is important. The prevention of hydrogen embrittlement can be done by adding some alloy like- Al, titanium and Mn.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] G. Gabetta, P. Cioffi, R. Bruschi, Engineering thoughts on hydrogen embrittlement, Procedia Struct. Integ. 9 (2018) 250–256.
[2] Jeffrey Venezuela et al., A review of hydrogen embrittlement of martensitic advanced high-strength steels, Corros. Rev. 34 (3) (2016) 153–186.
[3] Le Li et al., Effect of corrosion and hydrogen embrittlement on microstructure and mechanical properties of mild steel, Constr. Build. Mater. 170 (2018) 78–90.
[4] Yu. Matsumoto, Tomonori Miyashita, Kenichi Takai, Hydrogen behavior in high strength steels during various stress applications corresponding to different hydrogen embrittlement testing methods, Mater. Sci. Eng., A 735 (2018) 61–72.
[5] M.B. Djukic et al., Hydrogen embrittlement of low carbon structural steel, Procedia Mater. Sci. 3 (2014) 1167–1172.
[6] H. Barthélémy, Effects of pressure and purity on the hydrogen embrittlement of steels, Int. J. Hydrogen Energy 36 (3) (2011) 2750–2758.
[7] S.K. Dwivedi, M. Vishwakarma, Hydrogen embrittlement in different materials: A review, Int. J. Hydrogen Energy 43 (46) (2018) 21603–21616.
[8] Xinfeng Li et al., Effect of pre-strain on hydrogen embrittlement of high strength steels, Mater. Sci. Eng., A 616 (2014) 116–122.
[9] Tom Depover et al., Effect of hydrogen charging on the mechanical properties of advanced high strength steels, Int. J. Hydrogen Energy 39 (9) (2014) 4647–4656.
[10] J. Sanchez et al., Measurement of hydrogen and embrittlement of high strength steels, Eng. Fail. Anal. 59 (2016) 467–477.
[11] A. Roy, I. Manna, I. Chattoraj, Anomalies in hydrogen enhanced fatigue of a high strength steel, Int. J. Fatigue 59 (2014) 14–22.
[12] Ali Rajabipour, Robert E. Melchers, Service life of corrosion pitted pipes subject to fatigue loading and hydrogen embrittlement, Int. J. Hydrogen Energy 43 (17) (2018) 8440–8450.
[13] Seok Weon Song et al., Effects of carbon content on the tensile and fatigue properties in hydrogen-charged Fe-17Mn-xC steels: The opposing trends, Mater. Sci. Eng., A 724 (2018) 469–476.
[14] Jeffrey Venezuela et al., The influence of microstructure on the hydrogen embrittlement susceptibility of martensitic advanced high strength steels, Mater. Today Commun. 17 (2018) 1–14.
[15] Laurent Briottet et al., Fatigue crack initiation and growth in a CrMo steel under hydrogen pressure, Int. J. Hydrogen Energy 40 (47) (2015) 17021–17030.
[16] Motomichi Koyama et al., Overview of hydrogen embrittlement in high-Mn steels, Int. J. Hydrogen Energy 42 (17) (2017) 12706–12723.
[17] T. Doshida et al., Hydrogen-enhanced lattice defect formation and hydrogen embrittlement of cyclically prestressed tempered martensitic steel, Acta Mater. 61 (20) (2013) 7755–7766.
[18] T.C. Chen et al., The effect of phase transformation in the plastic zone on the hydrogen-assisted fatigue crack growth of 301 stainless steel, Mater. Charact. 112 (2016) 134–141.
[19] P. Fassina et al., Effect of hydrogen and low temperature on fatigue crack growth of pipeline steels, Eng. Fract. Mech. 103 (2013) 10–25.
[20] Yukitaka Murakami, Saburo Matsuoka, Effect of hydrogen on fatigue crack growth of metals, Eng. Fract. Mech. 77 (11) (2010) 1926–1940.
[21] https://www.corrosionpedia.com/articlelist.
[22] Xiaogang Li et al., Failure mechanism transition of hydrogen embrittlement in AISI 304 K-TIG weld metal under tensile loading, Corros. Sci. 130 (2018) 241–251.
[23] Kishi, A., and N. Takano. Effect of hydrogen cathodic charging on fatigue fracture of type 310S stainless steel. J. Phys. Conf. Ser. Vol. 240. No. 1. IOP Publishing, 2010.
[24] Mertens, Geert, et al. Hydrogen absorption and desorption in steel by electrolytic charging. Adv. Mater. Res. Vol. 15. Trans Tech Publications Ltd, 2007.
[25] Wayne R. Smith, Shiladitya Paul, Natural deposit coatings on steel during cathodic protection and hydrogen ingress, Coatings 5 (4) (2015) 816–829.
[26] S.K. Dwivedi M. Vishwakarma Effect of hydrogen in advanced high strength steel materials Int. J. Hydrogen Energy. 2019; 44(28007)-28030.
[27] Sandeep Kumar Dwivedi, Manish Vishwakarma, Siraj Ahmed, Experimental investigation of hydrogen embrittlement during coating process and effect on mechanical properties of high strength steel used for fasteners, Mater. Today. Proc. 5 (9) (2018) 18707–18715.
[28] Song J, Curtin WA. Atomic mechanism and prediction of hydrogen embrittlement in iron Nat. Mater 2013 Feb;12(2):145.
[29] C.J. McMahon Jr, Hydrogen-induced intergranular fracture of steels, EngFract Mech 68 (6) (2001) 773–788.
[30] S. Ramamurthy, A. Atrens, Stress corrosion cracking of high strength steels, Corrosion Rev 31 (1) (2013) 1–31.
[31] J. Venezuela, Q. Zhou, Q. Liu, H. Li, M. Zhang, M.S. Dargusch, et al., The influence of microstructure on the hydrogen embrittlement susceptibility of martensitic advanced high strength steels, Mater. Today Commun. 1 (17) (2018 Dec) 1–4.
[32] J. Venezuela, Q. Liu, M. Zhang, Q. Zhou, A. Atrens, A review of hydrogen embrittlement of martensitic advanced high-strength steels, Corros. Rev. 34 (3) (2016 Jun 1) 153–186.
[33] Lynch SP. Hydrogen embrittlement (HE) phenomena and mechanisms. InStress Corrosion Cracking 2011 (pp. 90–130).
[34] G. Lu, Q. Zhang, N. Kioussis, E. Kaxiras, Hydrogen-enhanced local plasticity in aluminum: an ab initio study, Phys. Rev. Lett. 87 (9) (2001) 095501.
[35] Lynch SP. Mechanisms of hydrogen assisted cracking–a review. Hydrogen effects on material behaviour and corrosion deformation interactions. 2003:449–66.
[36] M. Kappes, M. Iannuzzi, R.M. Carranza, Hydrogen embrittlement of magnesium and magnesium alloys: a review, J. Electrochem. Soc. 160 (4) (2013 Jan 1) C168–C178.
[37] K.A. Nibur, D.F. Bahr, B.P. Somerday, Hydrogen effects on dislocation activity in austenitic stainless steel, Acta Mater. 54 (10) (2006) 2677–2684.
[38] A. Atrens, Q. Liu, C. Tapia-Bastidas, E. Gray, B. Irwanto, J. Venezuela, Q. Liu, Influence of hydrogen on steel components for clean energy, Corros. Mater. Degrad. 1 (1) (2018) 3–26.
[39] T. Depover, D.P. Escobar, E. Wallaert, Z. Zermout, K. Verbeken, Effect of hydrogen charging on the mechanical properties of advanced high strength steels, Int. J. Hydrogen Energy 39 (9) (2014) 4647–4656.
[40] Danford MD. Hydrogen trapping and the interaction of hydrogen with metals. NASA Technical Paper 2744 (1987).
[41] Q. Liu, Q. Zhou, J. Venezuela, M. Zhang, J. Wang, A. Atrens, A review of the influence of hydrogen on the mechanical properties of DP, TRIP, and TWIP advanced high-strength steels for auto construction, Corros. Rev. 34 (3) (2016) 127–152.
[42] Tamarelli CM. AHSS 101: the evolving use of advanced high strength steels for automotive applications, 2011.
[43] D.H. Herring, Hydroqen embrittlement, Wire Form. Technol. Int. 13 (4) (2010) 24–27.
[44] J. Zhang, J. Zhu, S. Ding, L. Chen, W. Li, H. Pang, Theoretical models of threshold stress intensity factor and critical hydride length for delayed hydride cracking considering thermal stresses, Nucl. Eng. Technol. 50 (7) (2018 Oct 1) 1138–1147.

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