A review on the effect of microstructure on hydrogen induced cracking behaviour in pipeline and pressure vessel steels

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Abstract. Recently, the demand for energy is increasingly higher, and to meet the demand, more pipeline and pressure vessels are used to transport and store energy. Steels served in such environment need to have basic mechanical property, as well as excellent hydrogen induced cracking performance. Because hydrogen induced cracking failure will not only cause huge economic losses, but also have a harmful impact on the environment, it is necessary to study the impact of hydrogen induced cracking on steel and how hydrogen induced cracking occurs and expands. In this paper, the most important factor affecting hydrogen induced cracking, microstructure, was introduced.

1. Introduction
Currently, it is estimated that more than 10 billion tons of energy is consumed across the world every year, and fossil fuels, such as coal, oil and natural gas, provide over 80% of these energy. The increasing demand for oil and natural gas forces energy industries to search these energy in harsh environment. Undoubtedly, pipelines are often used to transport these resources over long distances and pressure vessels are applied to store energy[1]. Because most of these energy is rich in hydrogen, pipelines and some pressure vessels are inevitably exposure to sour environment, sometimes even high temperature and high pressure. During transportation or storage process, hydrogen atom would continuously diffuse into hydrogen traps in steel and form hydrogen molecule, and if the pressure resulting from hydrogen gas reached a certain critical level, crack would initiated. The phenomenon not only can produce great economic loss, such as repairing, maintenance or changing of pipeline steels in thousand kilometers, but also could pollute environment because of leakage of oil, petroleum, natural gas and crude oil to the grounds[2]. In the light of the damage, steels served in sour environment should have high strength and excellent toughness, especially the ability to resist the hydrogen induced cracking. In the past, many researchers conducted research aiming at enhancing the resistance to hydrogen induced cracking of pipeline steel and vessel steel to avoid the occurrence of failure in the oil and gas transport and storage[3,4]. It is reported that the HIC susceptibility of the steels is in close relation to several factors, such as their metallurgical structure, microstructure, grain boundary characteristics, inclusions and precipitates. To develop the intrinsic HIC resistance of steel, it is necessary to study the effect of each factor on HIC and mechanisms of HIC.
2. The effect of Microstructure on hydrogen induced cracking

Generally, there are many elements that can affect the hydrogen induced crack in steels, but it is no doubt that microstructure is one of the most important factors. High strength steel highly depend on heat treatment to meet mechanical requirement in the manufacturing process. Different manufacturing processes and heat treatment, such as thermomechanical control process (TMCP), quenching, quenching & tempering, normalizing, etc. brings in various microstructures, which further have different effects on the hydrogen induced cracking.

Studies found that soft phases, such as acicular ferrite, had low susceptibility to hydrogen induced cracking behaviour. Investigation by Gyu Tae Park et al. was mainly to compare the hydrogen trapping efficiency in different microstructures of pipeline steel of API X65 grade. Through the control of the start cooling temperature and the finish cooling temperature in thermomechanically controlled process, researchers obtained three different types of microstructure such as ferrite/degenerated pearlite (F/DP), ferrite/acicular ferrite (F/AF) and ferrite/bainite (F/B). These types of microstructure were shown in Fig.1. Studies found that microstructures such as DP, AF, BF and M/A constituents all can produce effects on both hydrogen trapping and hydrogen diffusion. The hydrogen trapping efficiency increased in the order of DP, BF and AF, with AF being the most effective type of microstructure. Although AF has the highest efficiency to trap hydrogen, which means a potentially hazardous site on crack occurrence, the HIC susceptibility of F/AF is lower than that of F/B. This phenomenon can be explained by high toughness of the AF hindering the crack propagation[5-9].

![SEM photographs showing the typical second phases and average ultramicro Vicker’s hardness values: (a) degenerated pearlite, (b) martensite/austenite (M/A) constituents, and (c) bainite.](image)

In discussing the effect of acicular ferrite on the hydrogen induced cracking susceptibility, Jing Li et al. also found that acicular ferrite could hinder the initiation and propagation of cracks. This is because the acicular ferrite phase has randomly-oriented grain boundaries and high dislocation density, and hydrogen can be trapped reversibly at the tangled dislocation in it, the hydrogen trapping efficiency of acicular ferrite higher than other types of microstructure. The results also were discovered that, compared with the steels with QF and the steels with LB + GB, the steel with AF+GB microstructure can obtain the combination of outstanding mechanical property and corrosion resistance to hydrogen...
induced crack, as the microstructure of acicular ferrite has high toughness to prevent the crack growth and propagation[5,10].

Soft phase such as quasi-polygonal ferrite and acicular ferrite can prevent the initiation and propagation of crack, while hard phase such as bainite and M/A islands is likely to generate harmful influence on hydrogen induced crack. When hydrogen atom were trapped at the bainite lath boundaries and the concentration of hydrogen reached a critical level, crack easily initiate at those hard phase. Researchers studied that the effect of three different types of microstructure of API X70 pipeline steel on HIC susceptibility, and these microstructure were obtained through different heat treatment including water-quenched, water-sprayed, and water-quenched and tempered. They found that all these steels were highly susceptible to HIC and the steel with martensite and retained austenite, only through quenching technique, was the most susceptible one. The steel of water-sprayed technique with acicular ferrite and bainite had highest hydrogen discharged content from reversible and irreversible traps[11].

Also, the M/A islands would be a preferential nucleation site of the hydrogen induced crack[12]. Studies found that the cracks in the steel with LB + GB microstructure propagate along the interface between bainite or M/A island and the ferrite matrix. In other words, the high concentration of mobile hydrogen in the reversible hydrogen trapping sites of steel with LB + GB microstructure reaches the critical level that can motivate the crack initiation and growth[10]. If more and relatively larger martensitic and austenite islands blocks existed in the microstructure of high grade pipeline steel, the susceptibility of hydrogen induced cracking can significantly increased. Martensitic and austenite islands(M/A) are hard phase which are mainly martensitic, and the hardness greatly differ from the matrix. Research discovered that micro-hardness value of the agglomerated M/A islands range from 294–330 HV and is higher than that of matrix. The size larger, the hardness value higher, and brittleness of the area greater[13]. Besides, in the wet H2S environment, massive hydrogen atom easily concentrate at the interface between M/A islands and matrix and further form into hydrogen molecule. As hydrogen pressure increased, crack can emerge and propagate along the interface between M/A islands and matrix. Besides, the rising number of M/A islands could result in the increase in phase transformation stress, and high inner stress generated in the steel, thus decreasing corrosion resistance of high grade pipeline steel[13,14]. To study the effect of M/A islands on HIC, Chen Jian et al. produced three steel samples including No.1, No.2and No.3, volume fraction of M/A islands of which was 17.4%, 2.1% and 0.75%, respectively. The HIC performance of No.1 and No.2 were both unqualified. For No.1, the poor HIC resistance was primarily as a result of the big volume and large size. Also, the addition of Mo promoted diffusion activation energy and decreased the diffusion coefficient of carbon, and higher content of solid dissolved carbon make M/A islands that were rich in carbon become crack initiation site. In No.2, the main reason for bad HIC performance was that M/A islands concentrate together and become large block[14]. Fig. 2 shows that the dislocation density of steels with microstructure of QF, GB + AF and LB + GB, respectively. In QF, the density of dislocation was the lowest, while GB + AF and LB + GB exhibit finer microstructure and high density tangled dislocations. In the steel with microstructure LB + GB, the high density dislocation around the crack propagation path permitted the accumulation of misorientations inside the grains, or distortion between neighbouring lattices, resulting in an improvement in HIC susceptibility.
3. Conclusions
In conclusion, this overview of the past research on the effect of these elements on HIC provide us with different perspectives to analyze the failure phenomenon.

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