Mechanistic Aspects of Hydrogen Damage in Fatigue Fracture of High Strength Bolt Steel

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ABSTRACT• *To examine a possible contribution of hydrogen on the crack initiation and propagation behaviour of high strength bolt steel, ASTM A490, fatigue tests was carried out under hydrogen environment. The conventional fatigue limit in air that is 300 MPa, disappears in hydrogen environment and shows unexpectedly low stress level around 50MPa at* 10^7 *due to the subsurface development of mechanistic damage caused by hydrogen. Test results show that fatigue-dominated mode of fracture at higher stress levels and the hydrogen-dominated mode of fracture at lower stress levels describe the nature of the fatigue fracture in hydrogen environment. Appearance of the QC facet on the fracture surface due to hydrogen should explain the initiation and propagation of the crack at the stress level far below the fatigue limit in air.*

INTRODUCTION

High strength steels show very high fracture sensitive property in hydrogen environment with an increase in strength level of the matrix structure [1-3]. Degradation of these high strength steels, AISI4340, ASTM A490, due to delayed fracture with a small amount of hydrogen from several ppm to several ten ppm, has been known as an unexpected premature fracture at extremely low stress levels, e.g. less than 1/10 of yield strength level [5-6]. A detailed examination of the occurrence of hydrogen related fracture phenomenon has been carried out on various types of specimens having sharp, blunt notch and even unnotched specimens [6]. These results revealed quite an essential process of crack development in the hydrogen charged high strength steels [5,6]. When we choose a sharp-notched specimen, the crack starts from the notch root with an intergranular(IG) mode of crack followed by the micro-void coalescence(MVC). On the other hand, however, in the case of unnotched specimen, the characteristic feature of crack development that can be read from SEM photographs, begins with quasi-cleavage (QC) cracking followed by IG crack and MVC leading to the final fracture of specimen [8]. This QC crack that initiates at subsurface of the specimen, can be a potential detrimental parameter in the fracture of high strength steels under applied load in aggressive environment.

Then, an essential nature of fracture events in high strength steels subjected to both fatigue and hydrogen attack was studied with an emphasis on the analysis of crack growth behaviour of quenched and tempered ASTM A490 bolt steel under push-pull fatigue cycling in hydrogen environment.

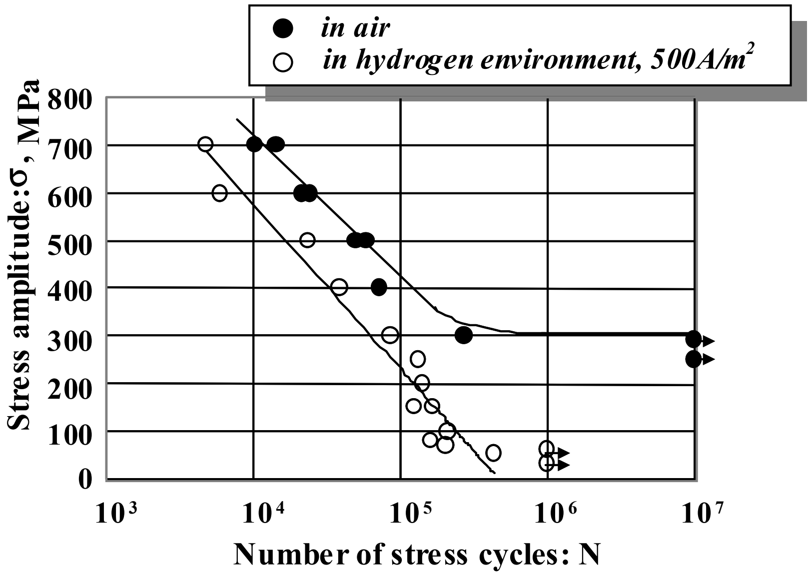
MATERIALS AND EXPERIMENTAL PROCEDURE

The material employed in this study was the high strength steel ASTM A490. This was machined into hourglass shape specimens with a 30mm radius and a mid-section diameter of 5mm and a total length of 100 mm. These were then quenched and tempered to have a yield strength level of 1400MPa and RA of 50%, respectively. Fatigue test was carried out with the MTS electro-hydraulic testing machine under pulsating frequency of 10Hz. Fatigue loading was broken off at 10^6-10^7 when the specimen was not broken. Cathodic charging of hydrogen during tests was kept constant in 1N H_2SO_4 with current density of $500A/m^2$. Furthermore, sustained load fracture tests were carried out under the condition that the hydrogen charging started concurrently with the fatigue loading and the loading was broken off at 10^4 min after the start of loading.

RESULTS AND DISCUSSION

Fatigue life curve in air and in hydrogen environment

Comparisons of fatigue tests were made between hydrogen charged and non-charged specimens as shown in Fig.1. A remarkable reduction in fatigue strength due to hydrogen can be seen in the lower stress range of the S-N curve. A SEM examination of the fracture surface show that the S-N curve consists of two fracture modes: one is surface crack development in the higher stress range and the other is the subsurface crack development in the lower stress range below the conventional fatigue limit. This



subsurface crack development is characterized by the QC facet mark, which shows that the fatigue crack behaviour is under the influence of hydrogen: the crack growth below the fatigue limit involves hydrogen-assisted growth of crack or delayed fracture. Then, the results of delayed fracture test of the same ASTM A490 were superimposed on the S-N curve in which the abscissa was transformed from [the number of stress cycles to fracture] to [the failure time] and in which the subsurface cracked specimens were identified with open marks as shown in Fig.2. The superposition of

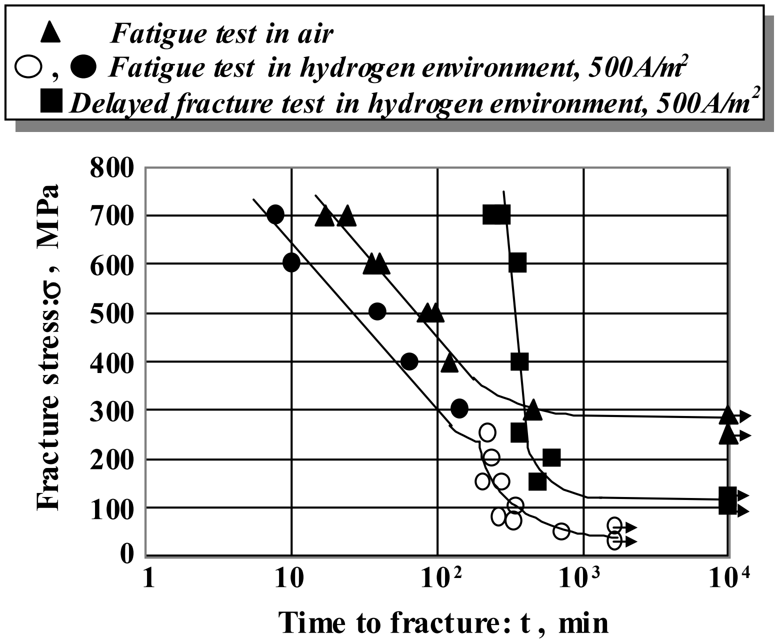


Fig.2. Superposition of the results of fatigue tests and delayed fracture tests.

two results evidently implies that not one but two types of fracture mechanisms are operative in the fatigue fracture of high strength steel subjected to hydrogen attack: the fracture above 300MPa seems to be influenced by the fatigue mechanism and that below 300MPa seems to be influenced by the hydrogen related delayed fracture. Figure 3 shows a schematic illustration of two types of cracking mechanisms operating in high and low stress levels respectively under hydrogen environment. This was studied with the aid of SEM fractography of respective specimens in the followings.

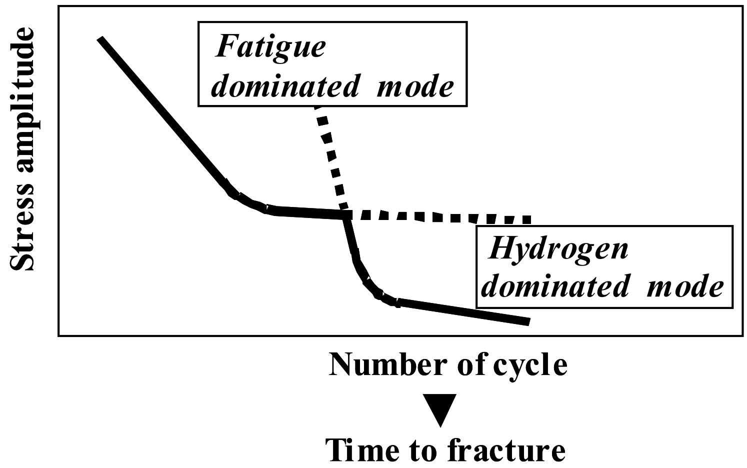


Fig.3. Two modes of fatigue crack development in hydrogen environment.

Two modes of crack initiation and propagation

The QC facet, as shown in Fig.4, that is a characteristic pattern of the

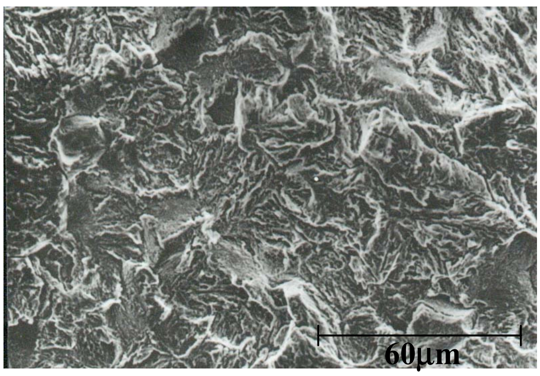


Fig.4. SEM photograph of QC facet on the specimen at 150MPa, N_f=168,420.

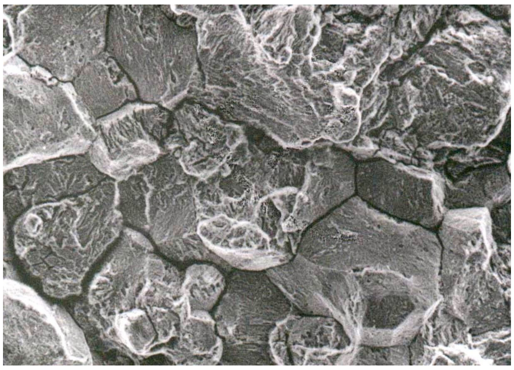
delayed fracture of hydrogen charged high strength steel, was clearly observed on the fracture surface of the specimen which was fatigue fractured at 150MPa, N_f=168,420. On the other hand, however, no QC facet was observed on the specimen fatigued above the 300MPa. Further fractographic analysis showed that IG crack, given in Fig.5 was observed in

60μm

Fig.5. SEM photography of IG facet at 300MPa, N_f=86,795.

the hydrogen charged specimen but not in the specimen with no hydrogen charging.

On the basis of these results and ordinary fatigue crack propagation



characteristics, it can be explained that crack propagation behaviour at the higher stress level above 300MPa is mainly dominated by the fatigue mechanism resulting in the development of cracks in the surface of the specimen with further propagation in either transgranular and/or intergranular mode. This fatigue-dominated mode of crack propagation may be accelerated with an influence of hydrogen. On the other hand at the stress level less than 300MPa, the morphology of crack propagation is quite interesting: the QC crack develops mostly at the non-metallic inclusion with stress-hydrogen interaction followed by transgranular and intergranular mode of propagation. This QC crack which was observed in the fatigue fractured specimen, has the same morphology as the one observed in the delayed fracture of hydrogen charged high strength steel. A schematic illustration of two modes of crack initiation and propagation in the fatigue under hydrogen environment are given in the Fig.6.

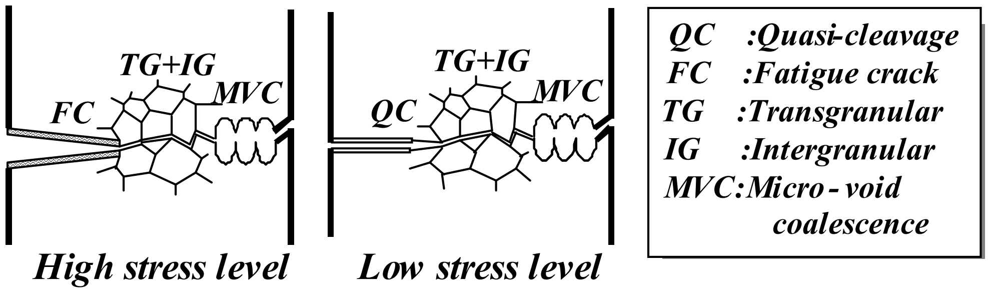


Fig.6. Models of fatigue crack development in hydrogen environment.

CONCLUSION

Mechanisms of the fatigue fracture of hydrogen charged high strength bolt steel ASTM A490 were studied with an emphasis on the two competing modes of fracture, fatigue dominated mode of fracture and hydrogen dominated mode of fracture. Results obtained are given in the followings.

(1) The fatigue limit of the Q/T ASTM A490 disappears and shows unexpectedly low stress level around 50MPa at 10^7 in the fatigue under hydrogen environment due to the subsurface development of mechanistic damage of hydrogen, i.e., the initiation and propagation of QC crack far below the conventional fatigue limit of 300MPa in air.

(2) Two competing modes of fracture exist in the crack growth process in fatigue under hydrogen environment: one is fatigue-dominated mode of fracture at higher stress levels and the other is hydrogen-dominated mode of fracture at higher fatigue cycling range of S-N curve.

(3) Fatigue-dominated mode of fracture is characterized by the development of crack in the surface, while hydrogen-dominated mode of fracture is characterized by the subsurface initiation of crack accompanying QC facet, which clearly suggests the contribution of hydrogen to fatigue at the stress level far below the fatigue limit in air.

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