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Evaluation method of sensitivity of hydrogen embrittlement for high strength bolts

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ABSTRACT

In this study, high strength bolts of 1100 MPa and 1300 MPa grades were charged with hydrogen to measure the sensitivity of hydrogen embrittlement (HE). Different levels of stress conditions based on various tensile stress and strain rates were applied. The bolts were then examined to see whether cracks were formed on the screw threads. The tensile stress and strain rate condition producing the most number of cracks on the screw thread of the bolt was decided as the most suitable test condition for the measurement of sensitivity of HE. For 1100 MPa grade high strength bolts, the most cracks were observed at the tensile stress ratio of 0.85 (load of 80 kN) and strain rate of $1.6 \times 10E{-}5$/s, while for 1300 MPa grades, the most cracks were observed at tensile stress ratio 0.87 (load of 100 kN) and strain rate of $1.6 \times 10E{-}5$/s. No cracks were found on the screw threads of bolt when the strain rate was increased over $8.3 \times 10E{-}4$/s.

1. Introduction

It is widely known that as the strength of a bolt increases, it becomes more sensitive to hydrogen related problems, thus limiting its application. Mechanical properties, such as a reduction area of ductile fracture, deteriorate drastically when hydrogen is introduced into steel. Especially, the higher the strength of steel, the more likely it is to cause the deterioration of mechanical properties by hydrogen, i.e. delayed fracture by hydrogen embrittlement (HE) [1,2]. Weld metal and heat-affected zones show clear degradation of mechanical properties by hydrogen as well [3–5].

There have been many reports on the causes of HE and one of the widely accepted theories is that HE occurs due to an internal flaw caused by hydrogen gas pressure. In other words, during metal manufacturing or processing, the oversaturated hydrogen inside the bolt is formed in molecular level as microscopic flaws applying hydrogen pressure, which in turn, leads to local tri-axial stress state. The movement of dislocations by the stress is then suppressed, weakening ductility, which eventually leads to fracture [6–9].

To date, the sensitivity of HE has been measured by using the following methods. One widely used method is to quantify the hydrogen content using the N.O.H elemental analyzer from a

Table 1
Chemical composition (wt%) of test sample.

Steel grade	C	Si	Mn	P	S	Cr	Mo	B
10.9 grade	0.22	0.23	0.83	0.009	0.007	0.81	–	0.0021
12.9 grade	0.33	0.23	0.67	0.012	0.005	0.97	0.18	–

Fig. 1. Jig for applying constant stress state during hydrogen charging.

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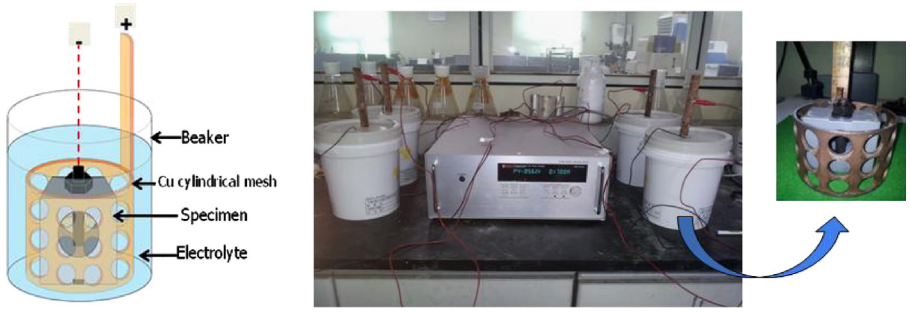

Fig. 2. A schematic illustration of a cell and a device for hydrogen charge.

Table 2
Hydrogen charging conditions.

Steel grade	Torque value (kgf cm)	Current density (mA)	Holding time (min)
10.9 grade	15	3.75	120
12.9 grade	17	4.25	120

Table 3
The configuration of Cd plating solution.

Solution	Elements	Amount
Cd plating solution	$Cd(BF_4)_2$	427 g
	NH_4BF_4	48 g
	H_3BO_4	21.6 g
	Metal Cd	20 g
	H_2O (distilled)	460 g
	pH	3–5

specimen with the size of $5 \times 5 \times 5$ mm^3 [10]. The other widely used method is to analyze intergranular fracture pattern by observing the fractography with SEM.

However, in case of high-strength plated fasteners, the former method is all but meaningless as the hydrogen on its surface is lost when the specimen is machined. Observing the fractography also presents difficulties in measuring HE sensitivity as it shows brittle fractures by intergranular fracture. Other methods are used to measure the HE sensitivity such as the evaluation of hydrogen delaying fracture method [11] and Thermal Desorption Spectrometry [12]. However, these two methods have an obstacle in adopting them in actual industrial sites as it takes two to three days to complete the measurement.

In this study, a new test method is suggested to measure the HE sensitivity by applying tensile loading at a slow strain rate.

2. Experimental procedure

2.1. Materials

The 10.9 grade bolt (1000–1200 MPa) and 12.0 grade bolt (1200–1400 MPa) that comply with ISO 898-1 designation [13] were used as test samples. The 10.9 grade was hexagon head type bolt (M12 × 80) while the 12.9 grade was a hex socket head cap type bolt (M12 × 80).

As shown in Table 1, chemical compositions of the bolts were analyzed by an Inductively Coupled Plasma-Atomic Emission Spectrometer (Model: LABTAM 8440). This analysis shows that the 10.9 grade was 5120 (boron steel) complying with ASTM A 1031 [14] while the 12.9 grade bolt was 4135 (SCM 435) complying with ASTM A 519 [15].

The tensile test of the bolts was conducted by a universal testing machine (Model: ZWICK Z 600).

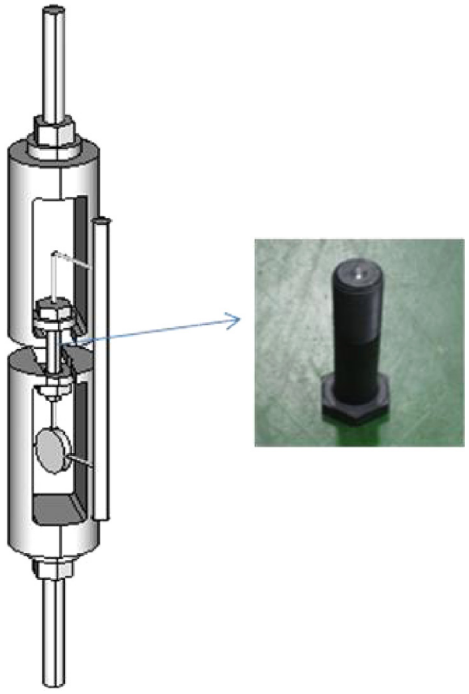

Fig. 3. A schematic illustration of a jig for applying tensile stress at various strain rates.

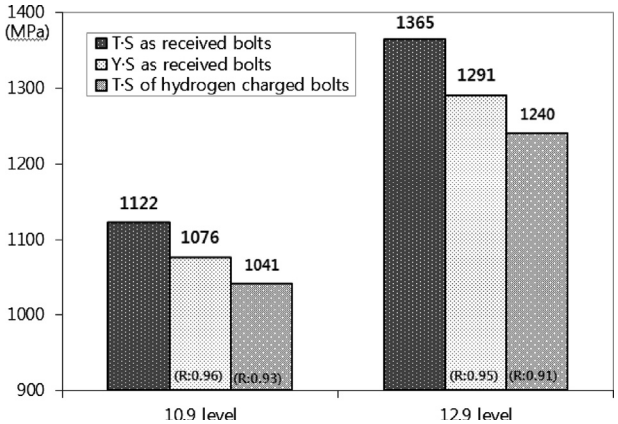

Fig. 4. The general tensile properties of bolt samples and tensile test results of hydrogen charged bolts.

2.2. Hydrogen pre-charging

A jig shown in Fig. 1 was manufactured to replicate the actual fastening condition used in the industry. The bolts were fastened at the point of their yield stress by using a digital torque wrench which is in accord to the general fastening method in the field.