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The effect of baking time, fillet radius, and hardness on the lifecycles of pole fastening screws in an electric motor with hydrogen embrittlement

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A B S T R A C T

In order to protect bolts from corrosion, electroplating such as zinc plating is widely used. However, hydrogen can easily penetrate or diffuse into the vacancies and dislocations between the lattices of bolt steel during electroplating. As the diffused hydrogen defects inside the lattice are in gaseous form, small cracks can easily be produced due to high pressure from the hydrogen gas. In this research, in order to determine the root cause of the fracture in pole fastening screws resulting from hydrogen embrittlement in typical electric motors, additional factors that accelerate hydrogen embrittlement fracture were selectively applied, including a small fillet in the head–shank transition and excessive hardness, and parametric study was performed experimentally.

1. Introduction

As the importance of clean technology such as electric automobiles has increased, the electric motor has been widely used in many industrial fields such as automotive, ship, mechanical industry and so on. However, since these motors are frequently installed in poor surrounding conditions such as high vibration, high temperature and high humidity conditions, design and evaluation of their reliability are crucial.

When a material exhibits hydrogen embrittlement, fracture occurs after a period of time—it could be a couple of days, months, or even years. Therefore, fracture caused by hydrogen embrittlement is called "delayed fracture," and it is not usually revealed in testing at the factory before the material is installed at the place of use. Fracture caused by hydrogen embrittlement can be found in various kinds of industries and has been extensively researched.

Ferraz and Oliver [1] reported the fracture of steel fasteners used for fixing an engine to its base. Looking at inter-crystalline fracture using scanning electron microscopy (SEM) analysis, the researcher found that it was caused by hydrogen embrittlement. In addition, through investigation on mechanical properties, it was found that excessive hardness also accelerated hydrogen embrittlement. Li et al. [2] investigated the relationship between hydrogen contents and the fatigue life of a test specimen of the high-strength spring steel 50CrV4. They suggested that the fatigue limit is a function of hydrogen contents and hardness, which revised Murakami's [3] research, where the influence of hydrogen on the fatigue limit was not

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considered. Nanninga et al. [4] found that elongation was reduced when pipeline steel exhibited hydrogen embrittlement. However, they also found that the yield and tensile strength of tested samples were similar regardless of the presence of hydrogen embrittlement.

The fracture of pole fastening screws used in the electric motor in this research was caused by hydrogen embrittlement occurring from the zinc electroplating process, which can be found through SEM analysis in Section 2. Hydrogen embrittlement can occur when the baking time of the bolt is not sufficient to remove the hydrogen after electroplating in accordance with ISO 4042 [5]. In addition, when the hardness is higher than the allowable limit (Hv 435 max. for 12.9 grade bolt) in ISO 898-1 [6] and the stress is severely concentrated in a small fillet or chamfer, the material can be more brittle, and fracture due to hydrogen embrittlement can be accelerated.

The U-bend method, which uses specimens of bent plates with various radiuses that are tightened with a bolt, and the drawn cup method, which used cup-shaped specimens drawn with the plate, are widely used to evaluate the hydrogen embrittlement of the plate [7,8]. In each of these approaches, the specimens are immersed in HCl solutions of various pH from 1 to 4 or NaCl solution of pH 7, and it is determined that no fracture will occur from the diffused hydrogen when specimens endure 96 h without fracture. The constant load tensile (CLT) test is widely used to evaluate the hydrogen embrittlement of rods, including bolts [8]. However, these evaluation methods are carried out under a static load. Therefore, in this research, the fatigue test is used to evaluate hydrogen embrittlement under a dynamic load.

Through this fatigue test, the effects of baking time, hardness, and the fillet radius of the screw, which allow estimation of accelerating factors of hydrogen embrittlement fracture of a pole fastening screw in a typical electric motor, are examined by experimental investigations. Through these experimental investigations, variations in the lifecycle of the screw in relation to hydrogen embrittlement will be discussed. The parameters taken into account will be the baking time, hardness, and fillet radius between the head and shank of the screw.

2. Material and method

The objective of this section is to investigate the failure mechanism of fracture occurring at the transition layer between the head and shank of a pole screw in a typical electric motor, as illustrated in Fig. 1.

2.1. Material

The pole screw in a typical electric motor studied in this research was manufactured based on ISO 898-1, with a diameter of 16 mm (M16), grade of stiffness of 12.9 grade, and 42CrMo4 material.

At first, the chemical composition analysis was performed. According to the chemical composition shown in Table 1, all chemical elements were within the specification range of the bolt material, 42CrMo4. With this chemical analysis result, one can ensure that the failure is not due to the improper chemical composition of the inherent material.

Zinc electroplating was applied to the pole screw in a typical electric motor in order to protect against atmospheric corrosion. It is well known that hydrogen release coincides with zinc deposition during zinc plating, and hydrogen embrittlement fracture is caused by cracks from diffusing hydrogen under high stress conditions. Therefore, a proper baking process involving an elevated temperature is usually required to remove hydrogen in the manufacturing process. In the following section, the possibility of the hydrogen embrittlement is analyzed through SEM.

2.2. Method

2.2.1. SEM

The analysis incorporated with SEM clearly showed that the crack propagation started from two particular regions along the outer diameter of the head-to-shank transition surface, depicted as "A" and "B" in Fig. 2(a). Fig. 2(b) and (c) shows SEM pictures of areas "A" and "B", respectively. Fig. 2(b)–(c) exhibits the crack lines spreading out from radial edge side toward the surface center with different contrast levels of the light and darkness.

When higher magnification SEM views (1000×) were observed, it was found that inter-crystalline subsidiary cracking features fade out toward the center of the bolt in area "A", as shown in Fig. 3, which indicates the fracture by hydrogen embrittlement. When the inclusion near the intergranular crack was investigated using energy-dispersive spectroscopy (EDS), as shown in Fig. 4, it was found to be composed of carbide; in addition, there were no abnormal chemical components causing the stress corrosion cracking except for hydrogen embrittlement. Moreover, a dimpled rupture fracture surface was observed in the center zone of the fracture surface, as shown in Fig. 5, which indicates ductile fracture. Thus, two different failure mechanisms could be identified on the fracture surface.

Since the material of the screw was high-strength steel and this could act as a brittle material under repetitive load in the elastic range, fatigue striations could not be precisely revealed in the SEM image. Therefore, the crack growth could not be defined exactly. However, through the fracture pattern on the edge and at the center of the fractured surface, the pattern of crack growth—including crack initiation and final rupture—could be estimated.

In short, based on SEM analysis, it can be assumed that the crack initiated from the two locations around the outer diameter of a surface with inter-granular fracture behavior; then, as the crack propagated toward the bolt center, the material