FAILURE ANALYSIS OF HYDROGEN EMBRITTLEMENT IN SHIP GEARBOX HEX BOLTS

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ABSTRACT

This paper presents the results of a failure investigation of hex bolts in a ship gearbox that failed during cruising. Failure analysis procedures were employed in this investigation. The results showed that the fracture occurred due to brittle failure. Voids were found on the fracture surface with intergranular cracks along with on metal grain boundaries. Hydrogen measurement was carried out and discovered that all the failed samples contained hydrogen in the range of 0.5 to 1.5 ppm. The chemical composition obtained showed that the bolts are low alloy steel with hardness greater than 30 HRC. It was concluded that the brittle failure of the hex bolts was due to hydrogen embrittlement. Hydrogen was produced during the corrosion process of the bolts and diffused into the voids. As a result, during mechanical loading, bolt strength and ductility both decreased.

Keywords: *Failure analysis; brittle; voids; intergranular; hydrogen embrittlement.*

1. INTRODUCTION

Gearbox components are commonly important and extensively used in many engineering systems. In a ship propulsion system, the gearbox is an essential component to transfer power from the main engine to the propeller. Gearbox systems contain meshing teeth on pinions and wheels to drive a shaft that allows speed to be increased or decreased based on operational requirements. Failure of a gearbox system not only results in replacement costs such as bearings or shafts, but can also affect the performance of the propulsion system (Charmont & Samroeng, 2013; Goran *et al.*, 2017; Onwuegbuchunam *et al.*, 2020). Previous gearbox failure studies have revealed that common components include not only shafts, bearings, bolts and gears, but also lubricants (Hassan & Alam, 2010; Weigang *et al.*, 2017). Axial cracks, macro pitting, scoring, wear, fretting corrosion, scuffing, misalignment and false brinelling are common failure modes on bearings and shafts (Charmont & Samroeng, 2013). A gearbox system can be fractured in a variety of ways including fatigue, brittle, ductile, mixed mode and shear fractures. Brittle fracture occurs quickly and with little deformation, whereas ductile fracture occurs slowly and with deformation before a part of the gear breaks. Mixed mode fracture refers to a fracture that is both brittle and ductile, while shear failure occurs when a line of force fails transversally rather than axially such as when a shaft twists. Fatigue is the formation and propagation of cracks as a result of repetitive or cyclic failure below the loads that would cause the materials to yield (ASM, 2005; Abdel & Mahmood, 2016).

In this paper, a study was carried out on a series of fractured hex bolts in a ship gearbox that failed during cruising. The hex bolts were used to connect the engine gearbox's outer shaft to the flange (Figure 1). The failed samples were thoroughly investigated in order to determine the cause of the failure.

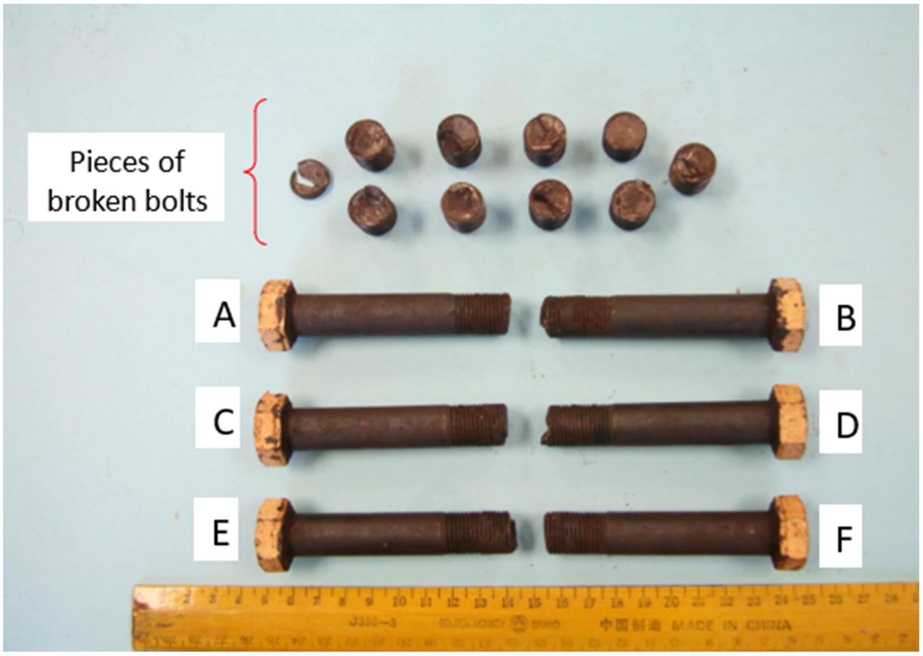

Figure 1: Six failed hex bolts, labelled as A, B, C, D, E and F, as well as pieces of ten broken bolts.

2. METHODOLOGY

Visual inspection of the samples was performed to acquire information on deformation and fracture surface (ASM, 1986; 1992; 1993). The samples were then cut with an abrasive cutter blade for additional analysis. After that, the samples were cleaned for 30 min in methanol using ultrasonic cleaning equipment. Macroscopic examinations were carried out with a Carl Zeis Stemi SV11 stereo microscope, with the post-processing images examined with an Axio Vision image analyser. Metallographic analysis was performed on the cross-sectioned samples of the fractured bolts. Grinding and polishing were used to prepare the samples, which were then exposed to 1% Nital etchant to disclose the microstructure. A scanning electron microscope (SEM) was used to examine the fracture surface at high magnification. A Wilson 2000 Series Rockwell hardness tester was used to measure the mechanical parameters of the samples' hardness (Figure 2). A Shidmadzu EDS 720 energy dispersive X-Ray fluorescent spectroscope was used to determine the chemical compositions.

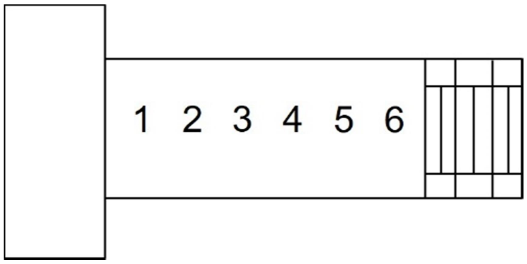

Figure 2: Locations of hardness testing on the failed hex bolt.

A Bruker G4 Phoenix DH hydrogen diffuser was used to measure hydrogen concentration. At high temperatures, this apparatus can detect hydrogen. Each fractured bolt was made up of two 3 g samples. In accordance with ISO (2018), the samples were placed in a quartz tube and heated to 400 and 600 °C. Hydrogen is released from the sample during the heating process and carried through the thermal conductivity cell with nitrogen as a carrier gas. The detector was then used a molecular sieve to filter out any interfering compounds, allowing only hydrogen to be measured.

3. RESULTS

3.1 Visual Examination

The fractured hex bolts were examined visually to study the failure mode. All the samples revealed that the external surfaces were rusted and the fractures took place in the threaded regions. Figure 3 shows the fracture surfaces of the bolts. The surfaces were found to be flat, with very little shear lip or plastic deformation. According to the examination, the flat areas that cover most of the fracture surfaces could suggest the brittle failure of the bolts. This failure demonstrates that the hex bolts failed suddenly with minimal elastic or plastic deformation before rupture.

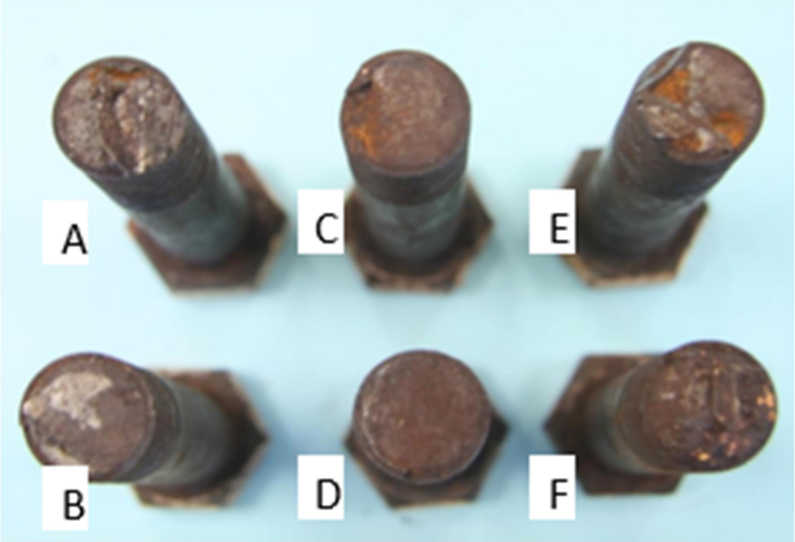

Figure 3: Fracture surfaces of hex bolts.

3.2 Macroscopic Examination

A Carl Zeiss Stemi SV 11 stereo microscope and Axio Vision software for image post-processing analysis were used out to enlarge the fracture surface. The examination shows that the regions of the flat zones are dominated on the fracture surfaces rather than the rough zones. The rough zones indicate that elastic or plastic deformation has occurred. The flat surface of brittle fracture is believed to be the source of the beginning of crack propagation. Due to low magnification of the macroscopic examination, no cracks were found on this flat zone. The images captured on the fracture surfaces of the failed hex bolts of samples B and D are shown in Figures 4(a) and 4(b) respectively.

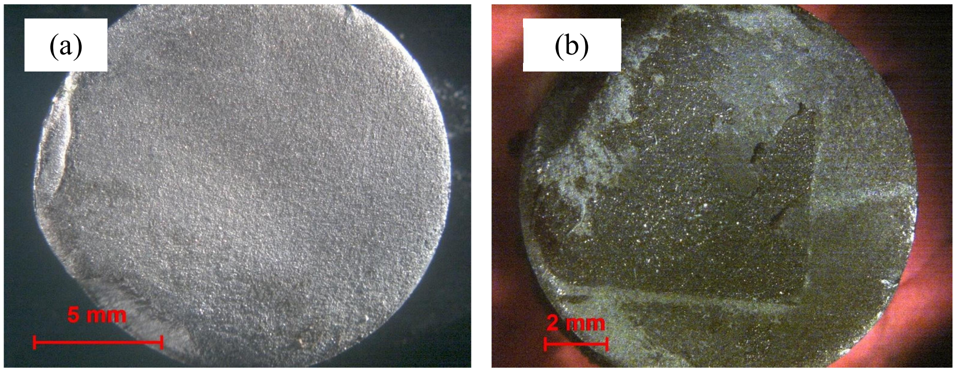

Figure 4: Macroscopic examination on the fracture surface of failed hex bolts: (a) Sample B (b) Sample D.

3.2 Microscopic Examination

The failed samples were examined under an inverted microscope for metallographic investigation and observation under higher magnification using a SEM. The images of metallography are shown in Figure 5. Observation of the microstructure found that individual and cluster voids with different dimensions are visible on the surface. The cluster voids (Figure 5(a)) with elongated and rounded shapes are approximately 200 µm. Figure 5(b) shows that elongated voids of approximately 60 µm in length. Further examination was carried out under higher magnification using the SEM to determine the location of voids in the microstructure. Based on SEM analysis (Figure 6), the voids occurred on the intergranular that can be observed on the grain boundary associated with the secondary crack, which is the effect of crack propagation from the intergranular. This intergranular cracking in the microstructure indicates the possibility of being caused by corrosion or hydrogen embrittlement (Sanchez *et al*., 2015; Le *et al*., 2018).

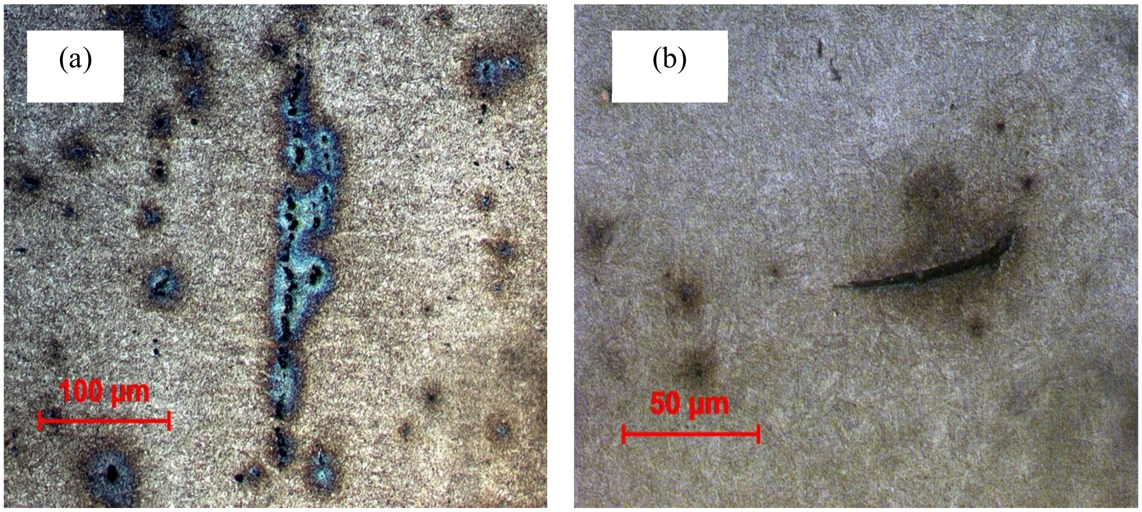

Figure 5: Images of microstructures of the failed samples: (a) A cluster of voids (b) Elongated void.

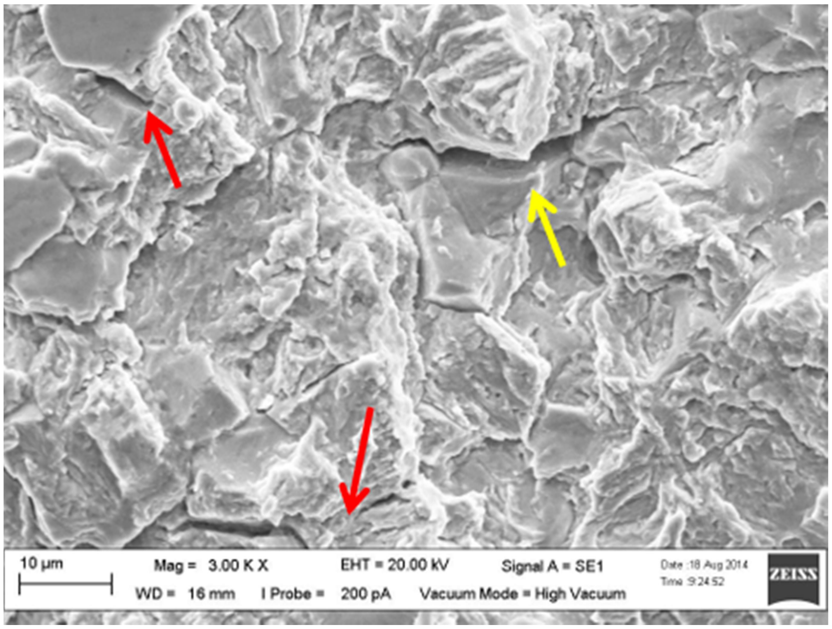

Figure 6: SEM image of the voids. The intergranular cracks are indicated by the red arrows while the yellow arrow indicates a secondary crack.

3.3 Materials Composition

Chemical analysis of the failed samples was carried out using a Shimadzu EDS 720 energy dispersive X-ray fluorescent spectroscope. The test results obtained are shown in Table 1. Based on the chemical analysis, the hex bolts were found to contain chromium (Cr), manganese (Mn) and carbon (C) as alloying elements with Iron (Fe) as a major element in the matrix alloy. The content of Cr and Mn in the steel alloy increases the resistance of the hex bolts to corrosion. The chemical composition results show that the hex bolts are suitable for use in the gearbox and are not the cause of the failure.

Table 1: Chemical composition of the failed hex bolts.

Element	Cr	Mn	C	Fe
Composition (%)	0.32	1.02	0.23	Balance

3.4 Materials Hardness

The hardness of the failed hex bolts was measured by using a Wilson 2000 Series Rockwell hardness tester. The hardness test was carried out in six different locations, with the results presented in Figure 7**.** The range of hardness obtained is 30 to 35 HRC. All the failed bolts show evenly distributed values of hardness except for Sample C, where the values are higher when close to the threaded region (Locations 4 to 6). The highest value of hardness is obtained for Sample B.

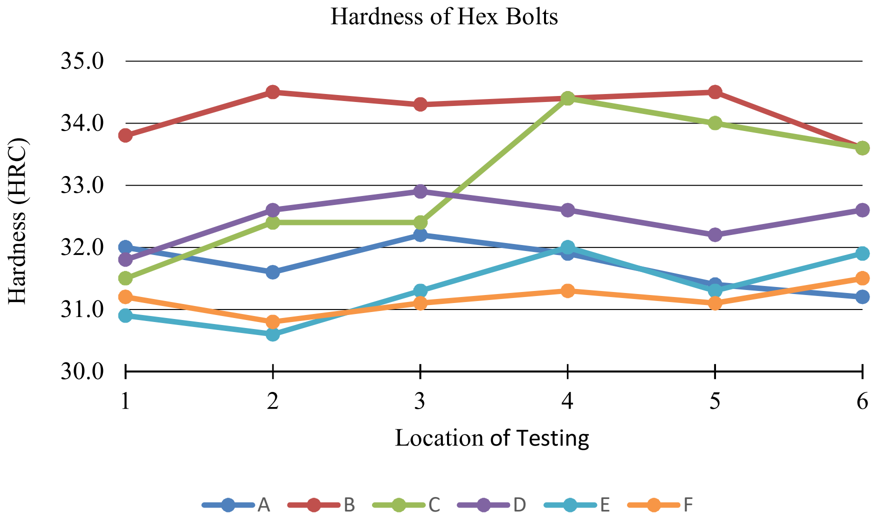

Figure 7: Graph of hardness testing results.

3.5 Hydrogen Concentration

Hydrogen content was measured to determine the concentration of hydrogen in the failed samples. The measurement was carried out using a Bruker G4 Phoenix DH hydrogen diffuser. The concentration of hydrogen was measured at temperatures of 400 and 600 °C. The sum of concentrations is shown in Table 2. The highest concentration of hydrogen was obtained for Sample F followed by Sample A with the values of 1.4216 and 0.5117 ppm respectively. The concentrations for Samples B, C, D and E are in the range of 0.1 to 0.4 ppm.

Table 2: Hydrogen concentration in the failed hex bolts.

Hex Bolt Sample	Parts Per Millions (ppm)		
	400 °C	**600 °C**	**Total**
A	0.4970	0.0147	0.5117
B	0.1327	0.2035	0.1362
C	0.2236	0.0601	0.2837
D	0.2214	0.1337	0.3551
E	0.2287	0.1033	0.3320
F	0.8577	0.5639	1.4216

4. DISCUSSION

According to the visual and microscopic examinations, the fracture surfaces of failed hex bolts revealed that the mode of failure was brittle. This is due to the evidence that most of the fracture surfaces were dominated by smooth and flat regions. The brittle failure shows that the hex bolts experienced sudden failure during operation with low intensity of elastic or plastic deformation (rough surface) before the final rupture. This type of brittle failure is undesirable in any mechanical system because it can occur suddenly and without warning, resulting in catastrophic or complete system failure (Bill, 2013; Knott, 2015).

Further investigations of the failed samples were carried out using microscopic examinations, which included metallographic analysis and SEM observation. On the flat regions of the failed samples, cluster and individual microvoids were clearly visible. These voids are believed to be manufacturing defects of the hex bolts. The rounded and elongated voids on the microstructure are the source of high stress concentration. This was widely assumed to be the cause of the failure. These voids exhibit as a crack initiation point and propagate when stress is applied during operation. Under high magnification using SEM, these voids are found between the boundaries of material grains. According to Amit (2017), this phenomenon is categorised as intergranular induced cracking, which occurs in the microstructure of hex bolts due to corrosion and hydrogen embrittlement. Sandeep & Manisah (2019) reported that hydrogen embrittlement can be attacked on the structure or mechanical system when these three factors exist, which are mechanical loading, high strength materials and external environment. The chemical composition in Table 1 indicates that the hex bolt is low alloy steel. The hardness values of the samples are above 30 HRC, indicating that this alloy steel is high strength material. Low alloy steel associated with high strength hardness is among susceptible materials to hydrogen embrittlement as well as nickel and titanium alloys (Motomichi *et al*., 2017; Enyinnaya & Ubong, 2018).

The hydrogen concentration was then measured, with Sample E having the highest value of 1.42 ppm. According to Murakami *et al*, (2010), hydrogen embrittlement can occur at a concentration greater than 1 ppm because hydrogen atoms can diffuse inside a material under atmospheric pressure. Hydrogen is diffused on the tip of voids in this case, which can reduce a material's cohesive strength and ductility.

5. CONCLUSION

The failure analysis was carried out on the failed ship gearbox hex bolts. The visual examination revealed that the failure mode was brittle fracture due to large areas of the flat surfaces as compared to the rough surfaces. Detailed analysis in the macroscopic examination showed that individual and cluster voids exist in the area of the flat zones on the fracture surfaces. Further examination using higher magnification during the microscopic examination indicated that intergranular induced cracking occurred along the material grain boundaries. The chemical composition of the samples showed that the bolts are low alloy steel, which contain Cr, Mn and C as alloying elements, with Fe as a major element in the matrix alloy. The hardness values of the failed samples were evenly distributed except for Sample C. The hydrogen concentration measurement demonstrated that the highest value was obtained for Sample F followed by Sample A. Based on the results of the investigation, it can be concluded that the brittle failure occurred due to hydrogen embrittlement and it was strongly believed that the hydrogen was generated from corrosion of gearbox bolts.

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