Failure Analysis of Hydraulic Rotary Drill Rods in a Limestone Mine

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***Abstract*—Failure analysis of two hydraulic rotary drills used for rock drilling was carried out. Chemical analysis, metallurgical examination, surface fractography and hardness measurement were used for the analysis. The failed drill rods composition matched with low alloy 31NiCrMo13-4 grade steel. The hardness measurement results suggested that the drilled rods were surface hardened. Surface fractography examination revealed that crack initiation of the fractured drill rods started at the outer surface, especially at the joint between the drill rod and drill bit. The mode of failure was found to be fatigue. The stress concentration locating at groove of threads at the joint was likely to cause the crack initiation. Propagation of fracture was observed with the evidence of beach mark, resulting from continuous nominal low stress.**

***Index Terms*—Failure analysis, surface fractography, fatigue, rotary drill, low alloy steel**

I. Introduction

Rotary drills are commonly used for blast-hole drilling in mining and quarry operations [1]. Rotary drills are capable of two methods of drilling. The majority of the drilling systems operate as pure rotary drills, driving fixed-type bits or tricone bits. The fixed-type bits have no moving parts and cut through rock by shearing it, thus they are limited to the soft rock and small holes (<4-inch diameter). Rotary crushing uses the tricone bits relying on crushing and spalling the rock. This is accomplished by transferring downforce, known as pulldown, to the bits. The other method, utilized by the rotary drill rigs, is called Down-the-Hole (DTH) drilling, which is not focused here. Rotation of the rotary drills is provided by a hydraulic driven gearbox, called a rotary head. A drill rod, coupled with a drill bit, is an importance part in the drilling systems. It functions as power or force transmitter from the power source to the drill bits.

Limestone is classified as sedimentary rocks, formed by an accumulation of sediments, such as corals and shellfish, in water and air with chemical action [1]. Chemically deposited limestone can be very tough rock to drill. In Northern Thailand, limestone mines can be found in Lampang province due to its high quality compared to other areas in central region. The limestone is supplied to cement production as raw material. As an environmental issue is concerned, a company operates a semi open cut type mining in Lampang, keeping surrounding scenery and reducing environment impact.

Crawler drills are used for 3 or 6-meter hole drilling before blasting in the mine. The drilling system is driven by a hydraulic powered rotary head, transmitting the power to a drill bit through a rotary drill rod [1]. According to its function, the rotary drill rod in the drilling system is required to meet the requirements. The drill rod is continuously experienced compressive and impact forces with torsion during operations. This may lead to failure of the drill rods, and subsequently the operation can be disrupted and increasing operation costs. A drill rod was failed for almost every two months.

In this study, two fractured rotary drill rods were analyzed. This investigation was to determine the cause of failure occurring in the hydraulic rotary drill rods.

II. Experimental Procedures

Field examination was conducted by site visiting to obtain general information such as specification of the drill rods provided by the supplier. Data collection, conditions of rock drill uses, locations of working site and operation lifetime, was carried out by interviewing the operators. The failed drill rods were collected from the semi open cut mining site located in Lampang province. EDM wire cut was used for the specimen preparations for further analysis. Chemical analysis was performed using a portable emission spectrometer (PMI-master plus). Rockwell scale C (Sonohard SH-75) was used in hardness measurement (ASTM E110-82). Surface fractography was examined using a stereomicroscopy and scanning electron microscopy. For metallography examination, the samples were ground and polished and etched with 2% Nital for 30 s. Optical microscopy was used for microstructure examination.

III. Results and Discussion

A. Field Examination

Interviewing the operators and data collection were conducted during the site visiting at the mine. Two failed drill rods analyzed were collected from the site within 5 months period. According to information from the machine manual, these drill rods were supplied and

Manuscript received March 5, 2016; revised October 20, 2016.

doi: 10.18178/ijmerr.5.4.251-254

imported from Sweden. As certified, drill rods were case hardened using carburizing method, but no details was provided. From site visiting, the working locations of the mine were divided into 5 zones with different altitudes between 370 - 480 m from sea level. This might affect the drilling condition. However, according to the data collected, the two drill rods analyzed were regularly used in operation over common areas, indicating that the drill rods were experienced in similar drilling conditions. In addition, no unexpected incidents were reported. The operation lifetime and rate of drilling of the analyzed drill rods was shown in Table I. The rate of operation was determined from the total drilling distances over operating time. The average operating time corresponded to total operating time over operation day. Both drill rods had been used in similar manner and were fracture at the coupling. The drill rods were threaded and coupled with the drill bits. Although the second drill rod (No. 2) was operated with higher operating time, compared to the first drill rod (No. 1), this had no effect on the operation lifetime.

Further data analysis, the operating times of the drill rods in each day were plotted against the consecutive operating day. The distributions of operating time of the drill rods were shown in Fig. 1. It can be suggested that the second drill rods (No. 2) were used in more intensive operations, comparing to the first drill rod (No. 1). The average operating time of the second was higher than that that of the first, resulting in a shorter period of use (32 days). Moreover the rates of drilling for each drill rod were analyzed over the operating time as shown in Fig. 2. It can be seen that the second drill rod (No. 2) was operated with relatively high drilling rate (>40m/hr) within 7 days before failure.

TABLE I. OPERATING INFORMATION AND LOCATION OF FAILURE

No.	Operation lifetime [hrs]	Rate of drilling [m/hr]	Average operating time [mins/day]	Location of failure
1	142	24.5	211	Drill rod/drill bits coupling
2	142	25.2	264	Drill rod/drill bits coupling

B. Chemical Analysis

The chemical composition of the failed drill rod is listed in Table II. This suggested that the drill rod were made from medium carbon steel low alloy. The composition was compared to the standard specification of DIN31NiCrMo13-4. This low alloy tool steel is generally used and similar low alloy grade tool steels are commonly used for piston and shaft [2]-[4]. The chromium content in the sample was slightly higher than that in the standard. The low nickel content in the sample could have resulted in no retained austenite after quenching. However, at this insignificant different level the effect might not be observed in this case. For bainitic steels, chromium increases the hardenability and hardness whereas nickel acts as austenite stabilizer and lowers the bainite transformation. However, the excess of chromium content can cause a decrease in ductility and transformation rate of bainite [5].

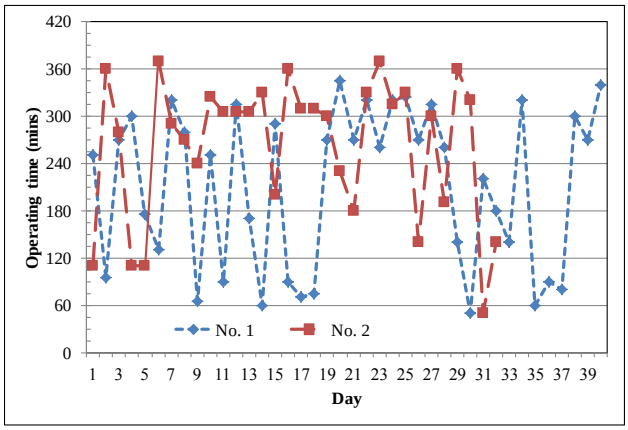

Figure 1. Distributions of operating time

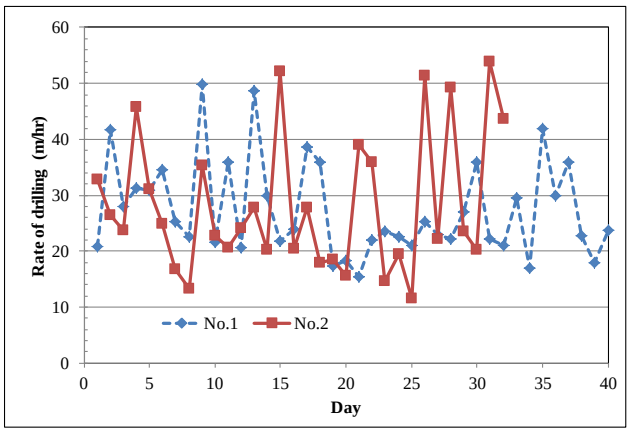

Figure 2. Distributions of drilling rate

TABLE II. CHEMICAL ANALYSIS RESULT OF A FAILED DRILL ROD

Element	C	Si	Mn	Cr	Mo	Ni
Standard	0.28-0.35	0.15-0.40	0.40-0.70	0.90-1.20	0.20-0.30	3.00-3.50
Sample	0.25	0.29	0.64	1.3	0.26	2.7

C. Hardness Measurement and Microstructure

Hardness measurements were conducted on two drill rod specimens at center (2 points) and near the surface (3 points) areas. Average hardness values in each zone are shown in Table III. It was clear that the hardness in near the surface zone was slightly higher than in the center, attributed to the carburizing surface hardening as per the design in the specification. The hardness lied within the specification of 38-42 HRC. Under a normal loading condition, a range of hardness value between 30-38 HRC of steel for forklift forks was reported to meet standard [6]. However, the surface hardness of the sample was quite low comparing with carburized 20NiCrMo2-2 low alloy steel (58-62 HRC) [2]. This low nickel-chromium-molybdenum with medium hardenability was used for pneumatic rock drill piston [2]. In reference [2], it was found that doubly higher chromium content and substantially lower nickel content, compared to the 20NiCrMo2-2 standard resulted in different microstructure, in other words, resulting in retained

austenite lied between martensite. There was no evidence of retained austenite observed in the sample due to insignificantly different from the standard.

The microstructure of the sample near the surface was examined by the optical microscope as shown in Fig. 3. It can be seen that the microstructure was bainite structure, consisting of alpha ferrite matrix (white) embedded with cementite (black). This was the result of carburizing surface hardening. The presence of hard cementite phase could lead to a brittle fracture. Compared to [6], the martensite structure was not observed after the surface hardening in the sample due to the low hardenability, low carbon content or unsuccessful surface hardening. As tempered martensite structure could also be observed in the low carbon content (0.2wt%C) steel alloy (18CrNiMo7-6 grade) [4].

TABLE III. HARDNESS IN THE CENTRAL AND NEAR THE SURFACE ZONE (HRC UNIT)

No.	Center	Near the surface
1	37.9	42.5
2	38.7	41.6

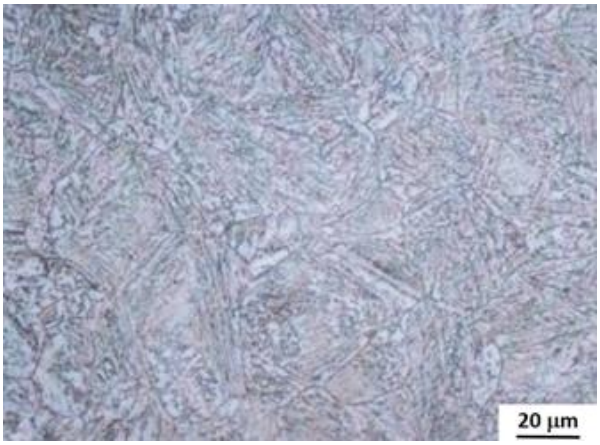

Figure 3. Optical micrograph showing bainite microstructure near the surface

D. Surface Fractography

The surface fractography examination of the failed drill rods was performed using stereomicroscope. In Fig. 4, it was clear that the initial point of the fracture was found at the outer surface at threads coupled with the drill bits. This normally acted as stress raiser, leading to stress concentration and crack initiation. The second cracking was also observed in the second drill rod (right), as the ratchet marks appeared similar to [6]. Additionally, the presence of the beach and ratchet marks indicated high local stress [7]. Based on information of the drills used in the operation, the second drill rods were intensively operated within a shorter period of time (32 days) and relatively higher rate of drilling, comparing to the first drill rod. Due to the high drilling rate, this might introduce the secondary crack in the second drill rod.

Fig. 5 shows the beach and ratchet marks appearing on the surface fracture. This is the evidence indicating that the failure was attributed to fatigue. It can be said that the fracture was in brittle mode as no plastic deformation was clearly observed on the fracture surface and no overload zone was observed.

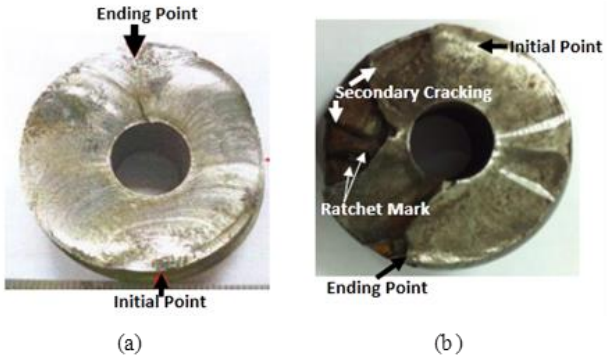

Figure 4. Overview of surface fractography of the fracture drill rods

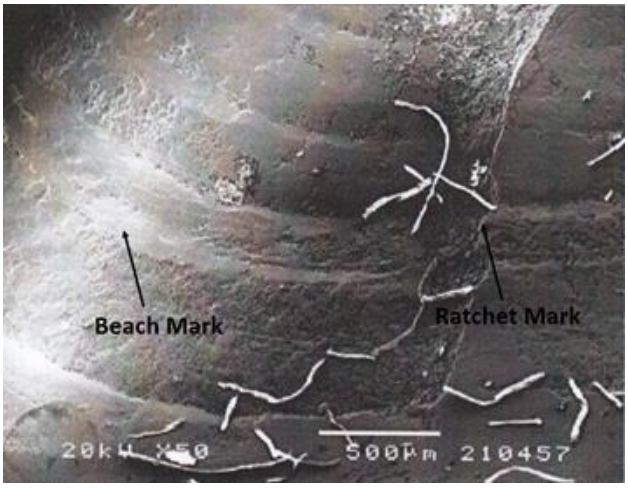

Figure 5. SEM Micrograph showing beach mark and rachet mark on the fracture surface

IV. CONCLUSIONS

In this study, the failures of rotary drill rods were analyzed. On the basis of the analysis results, it can be concluded as follows.

Two failed drill rods were used in similar and normal conditions and no unexpected incidents in operations were reported or found. The second drill rod was operated with higher rate of drilling. Both of failures were found to be at drill rod/drill bits thread coupling where crack initiation occurred. The chemical analysis indicated that the drill rods were made of case hardening low alloy 31NiCrMo13-4 grade steel with slightly high Cr content and low Ni content. The hardness was quite low comparing with case hardening 20NiCrMo2-2 low alloy steel. Stereography examination revealed that the presence of beach and ratchet marks on the fracture surface. This evidence suggested that the drill rods were fractured by fatigue. The crack initiation located at the groove of the thread coupling between the drill rods and the drill bit.

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