Failure analysis and revamping methods for loading threaded joints of raiseboring machine

Guoye Jing1,4, Fuwen Hu2, Yun Chen3
1Mine Construction Branch, China Coal Research Institute, Beijing 100013, China
2School of Mechanical and Material Engineering, North China University of Technology, Beijing 100144, China
3Ningxia Tiandi Benniu Industrial Group Co., Ltd., Shizuishan, 753001, China
4National Engineering Laboratory for Deep Shaft Construction Technology in Coal Mine, Beijing
Authors’ email addresses: jinggy@126.com; hfw@ncut.edu.cn; 15008621309@139.com

Abstract. The process of raise boring (or back reaming) has been successfully employed for vertical mine development. The technology has successfully evolved from early small borehole diameter less than 2m to large diameter greater than 8m without incident. However, in our developed raise boring machines, the threaded joints connecting reamers and drill rods suffered several fracture accidents during reaming in different geological and geotechnical conditions. Under this background, it is undoubtedly of great engineering value to explore the failure mechanisms and put forward systematic quality control and risk control measures.

The fractured threaded joints were visually examined on-site, and then examined in the laboratory using fractographic and metallographic examination, mechanical testing and chemical composition analysis. Firstly, the end faces of threaded joints could not to be installed to fit the end faces of spindles due to over-specified tolerances or insufficient preload. Secondly, it was found that the manganese (Mn) contents in material samples are higher than the national standards values. Thirdly, the heat treatment of water-quenching of workpieces perhaps caused a certain degree of residual stresses. Clearly this systematic inspection suggested we should take overall improvements to eliminate the potential failure mechanisms. After check and measurement of product and process performance, the cause-and-effect relationships undoubtedly were complex and multifaceted. Therefore, the component was redesigned using revamping methods including material compositions upgrade, fitting tolerances control, optimization of heat treatment process. Moreover, a systems approach and the institution of quality management system including increasing the preload, adding anti-dropping device and executing a Plan-Do-Check-Act cycle were implemented. Through this investigation and recommendations, the device has been in operation for more than two years without any problems.

1. Introduction
The process of raise boring (or back reaming) is a continuous, mechanical method of pumping and rotating the drillstring while simultaneously pulling out of the hole used for ventilation, access shafts, and ore and waste transportation for operating mines [1]. The method first starts by drilling a pilot hole generally with diameters from 280mm to 450mm to intersect the opening at depth up to 1000m [2].
Then this pilot drill bit would be removed and replaced with a reaming head. It has proved to be a very successful technique in underground mining operations with the maximum borehole diameter gradually increasing from less than 2m to large diameter greater than 8m without incident in the last more than five decades [3]. It is widely used in other underground engineering, such as hydropower stations, transportation, underground building, underground nuclear waste storages and military installations [4].

As the core equipment used in wellbore construction, there are many types of raise boring machines (RBM). During the pilot hole drilling cycle, drill rods connect the raise boring machine with a bottom-hole assembly consisting of ribbed stabilizers, roller reamer and pilot bit. After the pilot hole has been completed, a raise boring head is used to back ream the required raise between the underground levels. However, the requirement for back reaming is often not well defined and also the criteria to back reaming safety are not well communicated to the driller [1]. Lyle et al. [2] discussed the important considerations and engineering risk assessment methods for large diameter raise boring projects. James et al. [3] reported the investigation of the catastrophic failure of a raise boring machine due to the corrosion-induced fracture of the 32 drive head bolts. The cutting performance of raise bore machine is mainly dependent on geological features of rock, specification and design of the machine, and operational parameters such as force on cutter and rotary speed. Liu et al. [5] attempted to use explicit finite element simulation method to reveal the rock breaking mechanism process of the tipped hob cutter and the penetration depth of different rocks and the different broken state. The research work [6] developed empirical models to estimate the performance of RBM and operational parameters such as thrust and torque values of RBM.

Moreover, it should be pointed out that the most expensive item in raise drilling is neither the drill nor the reaming heads, but the string of drill rods [2]. The drill rods connects the reaming heads and the drill, and its main function is to transfer axial force, torque and bending moment, and deliver well washing fluids. During the back reaming process, the drill rod is suffering to the alternating load of axial force, torque, bending moment, shock vibration, friction and other additional loads caused by accident. Under the long-term effects of alternating loads and acidic corrosion in drilling fluids, especially under the transient load caused by countersinking and stuck drilling, the cracks in drill rods will appear, propagate until fracture failure. This transient break process is very short, without any macro precursors, and cannot be detected in time. Once it happens, the lower drill rods will fall into the pilot hole. Due to the strata compression and its own gravity, the salvage of drill rods would be expensive and time-consuming. Failure to salvage will cause the drill rods to be discarded in the pilot hole and bringing significant economic losses. According to statistical data in raiseboring engineering, 90% of drill rods fractures occurred in the joint part of the drill rods.

The loading threaded joint is at the lowest top of the whole drilling rig and is directly connected with the central sleeve of the reaming head. Compared with other drill rods joints, the tensile force, torque and bending moment of the loading threaded joint are the largest, especially the bending moment is the most serious. From October 2016, our developed raise boring machines of Tiandi Science and Technology Corporation, the threaded joints connecting reamers and drill rods suffered several catastrophic failures (sudden failure without warning) [7] during reaming in different geological and geotechnical conditions. Under this background, it is undoubtedly of great engineering value to explore the failure mechanisms and put forward systematic quality control and risk control measures.

2. Engineering context of fracture accidents

2.1 Production of threaded joints

The material of threaded joints (Figure1) is 42CrMo, a medium carbon alloy structural steel with good mechanical properties, good hardenability and wide application. 42CrMo steel has been widely used as forgings due to its ultrahigh strength, toughness, good hardenability, unobvious temper brittleness, and higher fatigue limit and resistance to multiple impacts after quenching and tempering. Most
important structural components were made by 42CrMo steel such as generator spindle, crane weight-on-wheel, automotive crankshafts, oil drill pipe joints of deepwell and armour materials [8]. These structures tend to trigger fatigue cracks during long-term service. If they are not discovered in time, the cracks will enlarge under the action of alternating loads and eventually cause crack failure, which seriously destroys the overall safety of the structures [9]. The heat treatment of threaded joints was cooled by quenching in water. However, since water-quenching usually causes the cracking of workpieces [10]. The production process and the controlled process parameters of threaded joints are listed as follows:

1) Forging shape.
2) Rough turning of end face, inner hole and outer diameter. The radial margin is controlled within 7mm to 8mm, and the end margin is controlled within 4mm to 5mm.
3) Surface flaw detection (magnetic particle).
4) Quenched-tempered heat treatment with the hardness HB300-340.
5) First fine turning with the radial margin of 2mm~3mm, the end margin of 1mm~2mm, and the 1:6 cone hole margin of 8mm.
6) Thread turning to ensure the size and roughness of the thread.
7) Finish turning of end face, inner hole and outer diameter. Machining the external gear teeth and measuring common normal to ensure the accuracy of teeth machining.
8) Quenching heat treatment of spline with the hardness HRC50-55. Phosphating treatment of threads.

Figure 1 Raise boring machine and the loading threaded joints

2.2 On-site investigation of fracture accidents
In our developed raise boring machines, totally seven threaded joints have been used in underground engineering. During boring operations with different coal mine shafts size, as shown in Figure2, four threaded joints fractured and the remaining three joints were not put into practical use. As mentioned above, the drilling tools of raise boring machines are used in series connection down from the threaded
joints, so every threaded joint is required for 100% safety and reliability. Clearly, cracks fracture accidents of threaded joints at work sites were extremely serious.

According to the visually and macroscopically observations and inspections from work sites, the transverse faces of threaded joints were not fitted closely with the transverse faces of main shafts, and this perhaps lead to the reduction of joint strength to some extent. The R6.35 fillet at the root of the thread is tangent to the fracture surface and there may be stress concentration. The floating sleeve is guided by the outer circle of the main shaft end and the ratchet sleeve. The inner hole is guided by the outer circle of the end of the bearing threaded joint, resulting in over-positioning. When the drill rod has a certain angle, the radial force of the drill rod may be transmitted to the load through the floating sleeve, and to the end of the threaded joint. Therefore, the threaded joints maybe suffered radical forces. Before the quenching and tempering treatment of the load-bearing joint, the remaining amount of the thread cone surface does not meet the requirements. The margin of a small segment exceeds 10mm, which may affect the even distribution of the thread load. The material of the bearing joint is 42CrMo, the original material is 40CrMnMo, and the performance is close. The toughness of the two materials is lower than that of 40CrNiMoA. Further in order to address the mechanism of failure, i.e. “how” this failure process occur [11], we still carried out systematic research to understand the most plausible root-cause [12].

![Figure 2 Cracks appearances of four threaded joints with their coal mine shafts size](image)

3. Experimental tests and analyses

3.1 Analyses of chemical composition

Took samples was from the threaded joints to test the chemical composition. The method of direct-reading spectrograph emission method (GB/T 4336-2016) is used for the analysis of metallic elements in threaded joints material samples. The results of two samples are shown in Table 1, which are referred to the China National Standards——GB/T 3077-2015 for structural alloy steels Alloy structure steels. Obviously, manganese (Mn) content is higher than the standard value. The effect of manganese in improving the mechanical properties of steel depends on its carbon content. When the carbon content is within 0.44%~0.56%, the increase of Mn content would reduce the ductility.
### Table 1 Chemical composition of materials

| Materials       | Chemical composition-quality factors (%) |
|-----------------|-------------------------------------------|
|                 | C   | Mn | Si  | S   | P   | Cr | Mo |
| #1 Tested sample| 0.44| 0.97| 0.25| 0.120| 0.019| 1.06| 0.27 |
| #2 Tested sample| 0.43| 0.97| 0.24| 0.003| 0.016| 1.05| 0.24 |
| Standard range  | 0.38-0.45| 0.50-0.80| 0.17-0.37| 0-0.035| 0-0.035| 0.90-1.20| 0.15-0.25 |

#### 3.2 Fractographic analysis

The recognition of fracture patterns is a morphological recognition process. Through a rigorous description of the fracture surface morphology, the fracture process can be clearly traced. From Figure 3, the fracture of #1 sample is relatively rough, fracture edges have obvious plastic deformation, and the interior has obvious arc trajectories and radial steps. The fracture surface of the sample is granular and relatively bright, mainly in the radiation area. The location of the crack source can be found along the arc trajectory.

The fracture of #2 sample is relatively flush and the color is relatively dark. The cracks are mainly distributed along the line. There are shiny facets and radial steps at the fracture. Residual macro plastic deformation near the steps is consistent with the characteristics of brittle fracture or low/limited ductility fracture. Brittle fracture is an extreme case of low/limited ductility fracture where the absorbed plastic strain energy is negligible [13].

![Figure 3 Fractograph of tested samples](image)

#### 3.3 Metallurgical structure analyses

The metallographic sample was taken at the location of the shown crack and the cross-section of the metallographic sample was ground and polished. And the cross section was observed with a metallographic microscope. After metallographic examination, as shown in Figure 4 and Figure 5, the metallographic structures of samples #1 and #2 are abnormal tissues after quenching and tempering, and the tissue distribution is very uneven. Observed at high magnification, the strip-shaped and acicular ferrite with obvious orientation characteristics can be seen. It is speculated that because the quenching and tempering process is not strictly controlled, the temperature in the high-temperature...
tempering stage is too high or the time is too long, so that martensite is decomposed into strip-shaped or acicular ferrite. The lamellar carbide is a brittle phase, which tends to produce a large stress concentration, which in turn leads to microcracks. The appearance of this abnormal structure can significantly reduce the hardness and mechanical properties of the material. In the expansion stage, the presence of cracks will cause stress and strain concentration on the surface of the threaded joint, thereby forming a fatigue source at the crack, and accelerating the generation and propagation of fatigue cracks [14].

3.4 Measurement of hardness gradient
According to the metallic materials Vickers hardness test standard GB/T 4340.1-2009, the microscopic Vickers hardness test was done to the sample. As illustrated in Figure 6, the hardness values of the tested points were HB258, HB258, HB247, HB253, HB253 and HB258, which were evenly distributed from outer circle of diameter 182 mm to the inner hole of diameter 70mm with 8mm interval. The real hardness values could not meet the design requirements HB280~320.
4. Revamping methods of quality improvement and risks control

Objectives of failure analyses Failure analysis has two main objectives. As mentioned above, sometimes the primary goal is to find the "root cause", which may be due to poor manufacturing, insufficient material selection at the design stage, or inadequate quality control. The second task is to take measures to avoid the identified “root cause” in the future, that is to ensure safe operation, and take accompanying measures if possible [15]. After check and measurement of product and process performance, the cause-and-effect relationships undoubtedly were complex and multifaceted. Therefore, we take necessary actions of failure prevention and quality improvement based on risk-based thinking.

4.1 Material upgrade
The bearing joint material 42CrMo is upgraded to 40CrNiMoA with better toughness. The hardenability of 40CrNiMoA is better than 42CrMo, and the comprehensive mechanical properties are also better [16].

4.2 Thread parameter adjustment
Special threaded connections require continuous optimization and improvement in dynamic applications, and are designed to reduce the maximum appearing stress peaks in the connection [17]. Galle et al. [18] argued that even by altering one single feature of the thread geometry, an improved structural integrity (e.g. fatigue resistance, leak tightness or collapse strength) can be obtained to withstand harsher conditions and greater loads. In our strategies, we first adjust the tight pitch of the thread, and change the tight pitch of the thread from a positive tolerance (+ 0.5 / 0) to a negative tolerance (0 / -0.5) to improve the preload ability of the tapered thread. Then we use straight spline or end spline to change the combined tensile and torsional force of the bearing joint to tensile and torsional transmission separation. In addition, we increase the arc of the root of the taper joint to improve the fatigue resistance of the thread.

4.3 Optimization of heat treatment process
In many cases, cracking occurs during the quenching process rather than after the quenching process, and this cracking is caused by transient stress rather than residual stress. We first improved the design of heat treated bar structure to avoid cracks at the root of the taper joint during heat treatment. When optimizing the rough machining of load-bearing joints, the thread should have a reasonable allowance and increase the fillet at the root. Secondly, we change the water-cooled quenching to oil-cooled...
quenching to reduce stress concentration. For carbon steel parts, due to the limitation of hardenability, water or water-based quenching agents should be used. However, when alloy steel is quenched, oil quenching is usually used. The cooling rate of the quenching oil is slower than that of water or water-based quenching agent, which ensures that the deformation of the part is small, thereby reducing other finishing difficulties. Finally, non-destructive testing of forgings must be performed after heat treatment.

4.4 Optimization of machining process

Improve the roughness of the root arc of the taper joint and the position of the undercut to ensure the surface accuracy of the undercut and the tolerance on the shape and position of the positioning surface.

4.5 Assembly and inspection

Appropriate preload force can increase the fatigue strength of load-bearing joints. Therefore, we increase the thread preload. Additionally we use anaerobic adhesive to prevent the threads from loosening. Periodic non-destructive testing and cleaning up the scum in the inner hole of the bearing joint are required to do. Ultrasound inspection of key positions between the shoulder surface of the bearing joint thread and the complete thread.

Besides the whole process quality improvement and control mechanism, we also take many risk prevention and control measures base on risk-based thinking. Risk-based thinking can provide the necessary methods to establish control and preventive measures to mitigate the risks caused by the unexpected results of the quality management system and obtain the maximum benefit from the opportunities that arise [13]. There we extra add anti-fall device. In the event of a fracture, the spring absorbs shocks to prevent the drill from falling. Regular replacement of threaded joints must be replaced normally after a certain period of service.

5. Conclusions

Failure analysis is a multidisciplinary and multifaceted scientific area that combines diverse fields such as fractography, metallography, chemistry, mechanics, design issues, non-destructive testing and others. This investigation of the catastrophic failures of loading threaded joints of raise boring machine fully demonstrated this point. We traced back to the origin, development (growth or propagation), and final ending stage of the cracks. And we systematically evaluated the potential root-sources and discussed potential failure mechanisms. Definitely, the fractures of loading threaded joints is determined as a fatigue fracture mainly suffering bending moment.

After root-cause analysis, we take corrective actions from two perspectives of quality control and risk prevention, to minimize the loading levels below fatigue limit, raise the safety factor and ensure reliable operation of the component. The most effectively corrective actions are to change the thread taper, pitch, interference or tolerances over the engaged threads to modify the load distribution and to reduce the stress intensity at the thread roots. Due to the limitations of fracture mechanics and quality control, we also have taken additional risk prevention measures such as anti-fall device and mandatory regular replacement. After the implementation of all the report recommendations, the raise boring machine has now operated without the catastrophic failures accidents of loading threaded joints for more than two years.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability statement

All data generated or analyzed during this study are included in this article.

Acknowledgments

The project was supported mainly by the National Key Researchand Development Program of China
(Grant No. 2016YFC0600802), and in part by the innovation and entrepreneurship project (Grant No. 2018-TD-MS009) of Tiandi Technology Co., Ltd.

References
[1] Yarim, G., Ritchie, G. M., & May, R. B. (2010). A guide to successful backreaming: real-time case histories. SPE Drilling & Completion, 25(01), 27-38.
[2] Lyle, R. R. (2017). Considerations for large-diameter raiseboring. In Proceedings of the First International Conference on Underground Mining Technology (pp. 581-595). Australian Centre for Geomechanics.
[3] James, A. (1997). Catastrophic failure of a raise boring machine during underground reaming operations. Engineering Failure Analysis, 4(1), 71-80.
[4] Liu, Z., & Meng, Y. (2015). Key technologies of drilling process with raise boring method. Journal of Rock Mechanics and Geotechnical Engineering, 7(4), 385-394.
[5] Hu, X., Du, C., Liu, S., Tan, H., & Liu, Z. (2019). Three-Dimensional Numerical Simulation of Rock Breaking by the Tipped Hob Cutter Based on Explicit Finite Element. IEEE Access, 7, 86054-86063.
[6] Shaterpour-Mamaghani, A., Bilgin, N., Balci, C., Avunduk, E., & Polat, C. (2016). Predicting Performance of Raise Boring Machines Using Empirical Models. Rock Mechanics and Rock Engineering, 49(8), 3377-3385.
[7] Chen, H., Lamei Ramandi, H., Walker, J., Crosky, A., & Saydam, S. (2018). Failure of the threaded region of rockbolts in underground coal mines. Mining Technology, 127(3), 146-154.
[8] Sun, C., Fu, P. X., Liu, H. W., Liu, H. H., & Du, N. Y. (2018). Effect of Tempering Temperature on the Low Temperature Impact Toughness of 42CrMo4-V Steel. Metals, 8(4), 232.
[9] Dong, J., Pei, W., Ji, H., Long, H., Fu, X., & Duan, H. (2020). Fatigue crack propagation experiment and numerical simulation of 42CrMo steel. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 0954406220910458.
[10] Liu, Y., Zhang, J., Qin, S., Zuo, X., Chen, N., Gao, F., & Rong, Y. (2019). Investigation of quenching stress of 42CrMo treated by alternately timed quenching process. Heat Treatment and Surface Engineering, 1(1-2), 23-31.
[11] Pantazopoulos, G. A. (2014). A Process-Based Approach in Failure Analysis. J Fail. Anal. and Preven. 14, 551-553.
[12] Peng, C. H., Liu, Z. Y., & Wei, X. Z. (2012). Failure analysis of a steel tube joint perforated by corrosion in a well-drilling pipe. Engineering Failure Analysis, 25, 13-28.
[13] Pantazopoulos, G. A. (2019). A short review on fracture mechanisms of mechanical components operated under industrial process conditions: Fractographic analysis and selected prevention strategies. Metals, 9(2), 148.
[14] Hongfei, G., Yan, J., Zhang, R., He, Z., Zhao, Z., Qu, T., ... & Li, C. (2019). Failure Analysis on 42CrMo Steel Bolt Fracture. Advances in Materials Science and Engineering, 2019.
[15] Zerbst, U., Klinger, C., & Clegg, R. (2015). Fracture mechanics as a tool in failure analysis—Prospects and limitations. Engineering Failure Analysis, 55, 376-410.
[16] Dejun, K., & Lei, Z. (2014). Effects of laser quenching on impact toughness and fracture morphologies of 40CrNiMo high strength steel. Journal of materials engineering and performance, 23(10), 3695-3702.
[17] Van Wittenbergh, J., De Baets, P., De Waele, W., Galle, T., Bui, T. T., & De Roeck, G. (2011). Design characteristics that improve the fatigue life of threaded pipe connections. In Sustainable Construction and Design 2011 (SCAD) (Vol. 2, No. 2, pp. 334-341). Ghent University, Laboratory Soete.
[18] Galle, T., De Waele, W., De Baets, P., & Van Wittenbergh, J. (2011). Influence of design features on the structural integrity of threaded pipe connections. In Sustainable Construction and Design 2011 (SCAD) (Vol. 2, No. 2, pp. 237-245). Ghent University, Laboratory Soete.