China Steel Technical Report, No. 36, pp.114－119, (2023)

Premature Failure Analysis of Mill Rolls at China Steel Corp.

YI-LIANG CHENG, PING-HSUN TSAI, HSIN-JUNG HSIEH,
YI-LIN CHIU and CHUNG-HO KO

Plant Engineering & Maintenance Department
China Steel Corporation

The premature failure of mill rolls can be costly not only due to its high initial cost but also the huge cost of rolling mill downtime. In this paper, a backup roll with a fractured roll neck in a temper and recoil line is investigated. To identify possible root causes, loading patterns of the rolling process, detailed fracture characteristics, and propagation direction of the premature fractured roll were inspected, while a high-stress spot at the roll neck during the normal rolling process was evaluated by the finite element method (FEM). The results revealed that such premature failure was unlikely to be caused by stress behavior under normal rolling, but corrosion pitting pits clustered around the roll neck surface could induce high-stress concentration under such circumstances and facilitate overloading damage. In addition, the corrosive element intruded upon the roll neck surface due to the crevice corrosion between the backup roll and the press-fitted thrust ring was strongly in doubt. The corrosion effect seemed to be accelerated by some obvious residual tooling marks at the roll neck surface. We therefore propose several countermeasures to prevent and/or terminate such failure mechanisms in time to extend the life of mill rolls.

Keywords: Failure Analysis, Mill Roll, Fracture, Corrosion

1. INTRODUCTION

Rolls are used to reduce the cross-section and shape of the rolled material. They experience high stress and wear during operation. Despite careful manufacturing and rolling practices, rolls may still prematurely fail in service, leading to partial or total loss of the rolls and even subsequent damage to rolling equipment. When this happens in the CSC group, it's important to determine the root cause and improve it to prevent reoccurrence. In this paper, a backup roll fractured at the roll neck in a temper and recoil line is investigated.

The 4-Hi rolling mill of a Temper and Recoil Line (TNRL) is commonly used to handle hot-rolled coil. It can improve the shape and mechanical properties of the strip. The top backup roll of the 4-Hi mill broke around the drive-side (D.S.) roll neck during normal operation at a TNRL of the CSC group. This had never happened before and caused significant productivity loss in the mill. To avoid similar accidents reoccurring and prevent the consequent issues at other mills, it is necessary to identify the main problem in this event and make improvements immediately. Figures 1 (a) and (b) show the location and actual situation of the broken roll, respectively.

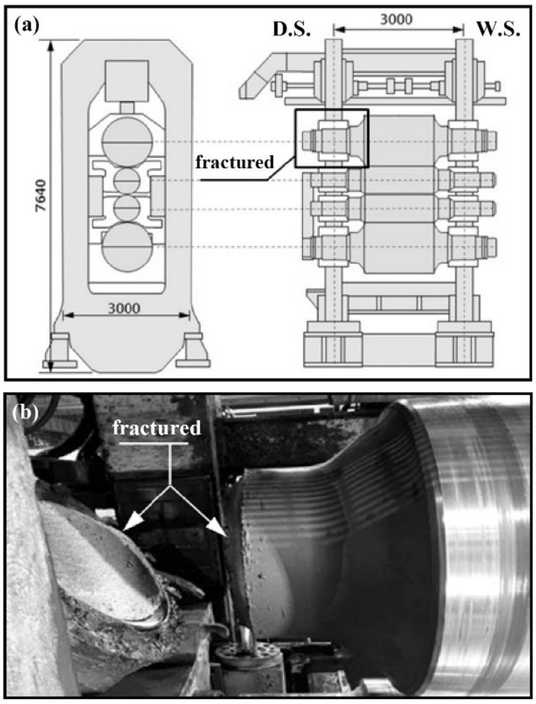

Fig.1. The location (a) and the appearance (b) of the broken roll.

2. ANALYSIS METHOD

2.1 Recheck Production Data

When premature roll failure occurs, such as fracture, spalling, or any kind of abnormal marks on the barrel surface like fire cracks, overwear, pinholes, etc., the related production data shall be reviewed, including product information, rolling parameters, roll grinding history, supplier's inspection report, special events record of the roll's rolling history, and any other data that may have caused the failure. This could help the specialist in roll failure analysis examine the roll maintenance and rolling conditions. Besides, to save analysis time, only critical data needs to be inspected when the fracture characteristics and failure mechanisms are evident based on reference cases or CSC's experience.

2.2 Visual Examination of Fracture Parts

Visual examination is the most practical on-site failure analysis method. It is based on fractography that studies how cracks nucleate and grow microscopically to cause macroscale fracture. If the specimen is well preserved and the analyst is knowledgeable, the fracture appearance reveals details of the loading events that culminated in the fracture(1). Furthermore, it is commonly used to trace the fracture origin and infer the root cause.

2.3 Evaluate the Stress of Roll

The roll neck fracture might result from overloading. In this paper, the mechanical design software (Autodesk Inventor) and finite element analysis software (MSC Marc) are used to check if the applied roll force will cause the stress in the roll neck to exceed the strength of the roll material.

2.4 Nondestructive Testing (NDT)

Liquid penetration testing (PT), magnetic testing (MT), and ultrasonic testing (UT) are the most frequently used NDT methods in roll failure analysis. PT and MT can be used to detect surface defects. UT can not only find internal defects but also trace the surface initial crack from spalled areas. If detected defects match the fracture origin, this shall be the cause of roll failure.

3. RESULTS AND DISCUSSION

3.1 Recheck Production Data

According to production records, the backup roll was fractured while rolling carbon steel (JIS G 4051 S50C) with a width of 1060mm. The operation records showed no production accidents like cobble or rolling double plate, etc., before failure. The roll force, speed, and other parameters were normal and similar to previous rolling of the same product.

The specifications from this backup roll design drawing allow 1500 tons of roll force and 600 m/min of speed respectively. Its total length is 4400mm, barrel length is 1600mm, new roll diameter is 1200mm and scrap diameter is 1100mm. It means the outer surface allows 50mm of grinding thickness. The material is double-poured cast iron with hardness Hs 70~75 on the shell (barrel surface) and Hs 35~40 on the core (journal).

This fractured backup roll was purchased in 1998. The Supplier's inspection reports met CSC's request specifications. The fractured diameter was 1152.3mm, using only 23.85mm (47.7%) of the grinding allowance.

Figure 2 shows the rolling and grinding history over the last 7 campaigns. The average monthly rolling tons in this campaign wasn't the highest, and the trend of diameter variation revealed no over-grinding from rolling accidents.

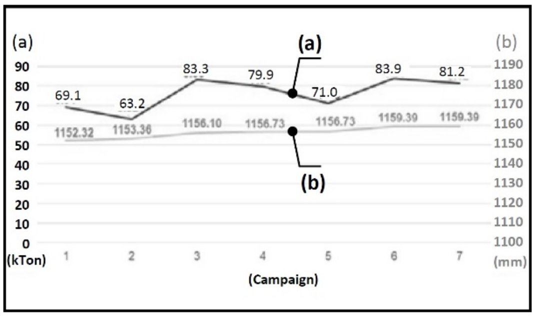

Fig.2. (a) The average monthly rolling tons of each campaign and (b) the decreasing trend of grinding diameter.

The examination while grinding such as barrel profile, eddy current test, hardness, etc., all met the control value. It can be judged from the above that the maintenance status of this backup roll was good.

3.2 Visual Examination of Fracture Parts

The fractured backup roll was separated into two parts. Part A was designated for the larger piece and Part B was the smaller piece. Their fracture surfaces were not like any visually identifiable arrest marks, such as ratchet marks, beach marks, radial marks, or chevron marks[2] as shown in Figures 3 (a) and (b). The fracture propagation direction could not be determined and hence we can't find the initial point to infer the root cause.

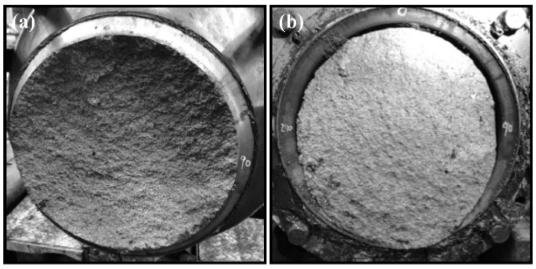

Fig.3. Fracture surface of (a) Part A and (b) Part B.

Using the fractography atlas is another way to determine the root cause. By comparing Figures 3 (a) and (b) to the fractography atlas of the ASM Handbook (Fig.4) and the CSC's roll failure database (Fig. 5), the premature failure possibility of the backup roll from rotating bending fatigue or internal manufacturing defects could be excluded.

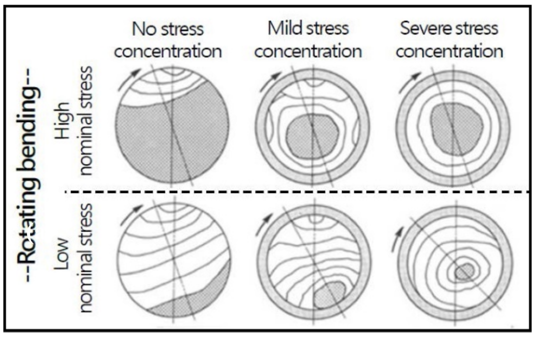

Fig.4. The fractography atlas of rotating bending fatigue.

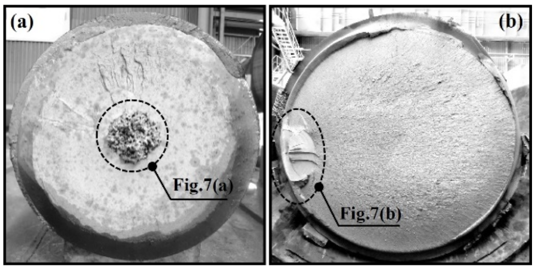

Fig.5. The fractography atlas of a manufacturing defect, (a) Example 1 and (b) Example 2.

Figures 6 (a) and (b) show the appearance of Part A and Part B. The fracture surface is plain and presents a single angle with a roll axis. In Figure 6 (b), the side of the fracture is at the roll neck fillet and the other at the larger diameter. Based on finite element analysis (FEA) experience, the maximum stress located at the roll neck fillet is more possible than at the bigger diameter. It is speculated that the fracture surface started at the roll neck fillet and ended at the bigger diameter, as the arrows shown in Figures 6 (a) and (b).

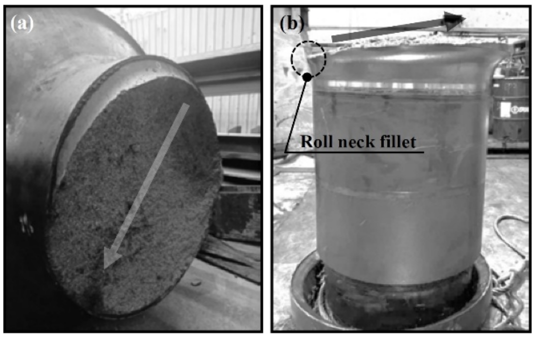

Fig.6. Fracture appearance of (a) Part A and (b) Part B.

Additionally, the fracture appearance also provided another piece of evidence to enhance the inference that premature failure didn't result from rotating bending fatigue fracture or manufacturing defects inside the roll. In rotating bending fatigue fracture, the surface will not present a single angle, it will start at the outer diameter circumference, propagate toward the center, and show a rapid fracture area, as shown in Figure 5. When the roll fails due to manufacturing defects, the fracture surface won't present a plain surface, it will have a large variation at the initial point (Fig.7. (a)) and may find the arrest mark like the beach mark, as shown in Figure 7 (b).

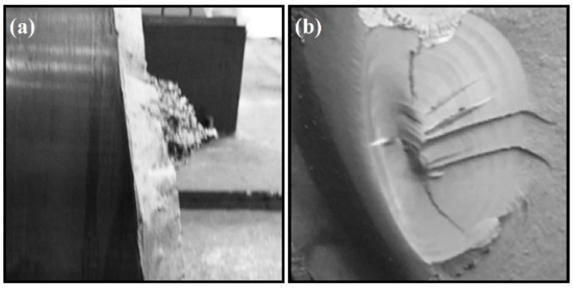

Fig.7. Zoom in the manufacturing defects of Fig.5. (a) and (b)

3.3 Evaluate the Stress of Roll

The fracture appearance shows that the loading mode of roll failure isn't fatigue but overload. To evaluate the stress of the roll, mechanical design software (Autodesk Inventor) and finite element analysis software (MSC Marc) are used. Figure 8 (a) shows the free-body diagram of the backup roll during rolling. The distribution load equals roll force divided by the contacting length with the work roll, while the center line of the fix-end bearing and free-end bearing are pin support and roller support respectively. The result calculated by Autodesk Inventor shows that the maximum stress is located on the fillet of the roll neck. It matches the speculation in the previous visual examination, but the maximum stress is only 73 MPa, it didn't exceed the tensile strength (430~485 MPa) of the roll material.

An MSC MARC fine-mesh model was created to re-evaluate the stress of the fillet. The analysis results show that the maximum stress is also located at the fillet, but the value less than 100 MPa still didn't exceed the tensile strength, as shown in Figure 9.

According to the above analysis, only the roll force can't cause overload failure. It's implied that if no production accidents were found in the previous inspection of the operation record, then there should be some stress concentration factors, like machining flaws, repair welding defects, etc., on the roll neck surface to promote premature failure.

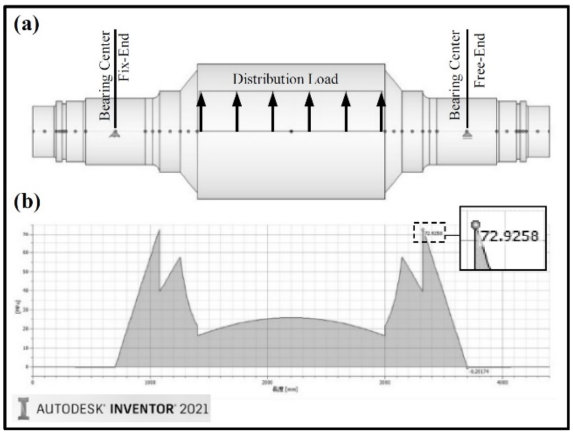

Fig.8. The stress calculated by Autodesk Inventor (a) model and (b) results.

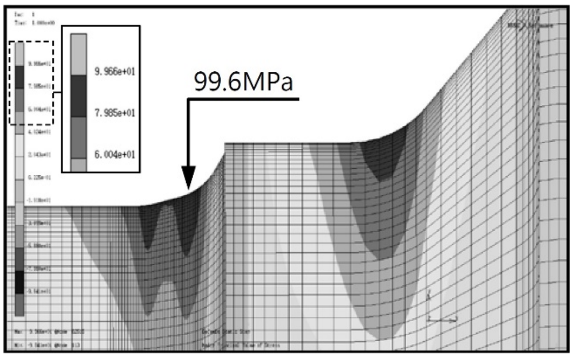

Fig.9. The FEM result of the fillet of the top BUR.

Figures 10 (a) and (b) show the simulation results of different artificial defects at the roll neck fillet.

If there is a 1mm wide and 1mm deep artificial defect in the whole circumference of the roll neck fillet, under the same load and boundary condition, the stress of the fillet will increase approximately 3.7 times (from 99.6Mpa to 376Mpa) as shown in Figure 10 (a). The stress will exceed the tensile strength (430~485 MPa) of the roll material while the depth of the artificial defect is over 5mm as shown in Figure 10 (b). These results mean the smooth propagation area of the fractured surface can only be observed within 5mm, and explain why the fractured surface was almost all rough and fast-breaking.

3.4 Nondestructive Testing (NDT)

To inspect the defects on the roll neck surface, liquid penetration testing (PT) was used. The test method followed the CNS-11225 standard with Magnaflux SKL-WP2 penetrant and Magnaflux SKD-S2 developer.

Figure 11(a) shows the PT results of the roll neck surface of Prat A. The defects like cracks and micro-holes scattered around the roll neck surface were found as shown in Figure 11(b) and some cracks even connected to the fracture surface as shown in Figure 11 (c).

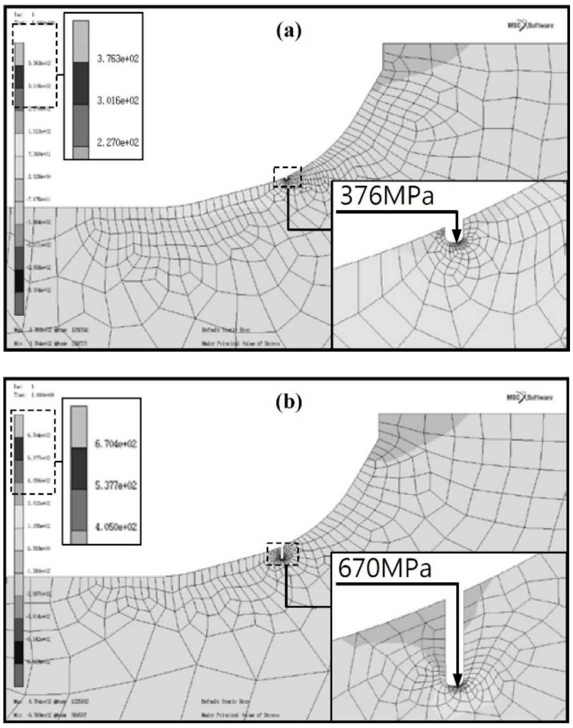

Fig.10. The FEM results of the backup roll with artificial defect, (a) width 1 mm/depth 1mm and (b) width 1 mm/depth 5mm

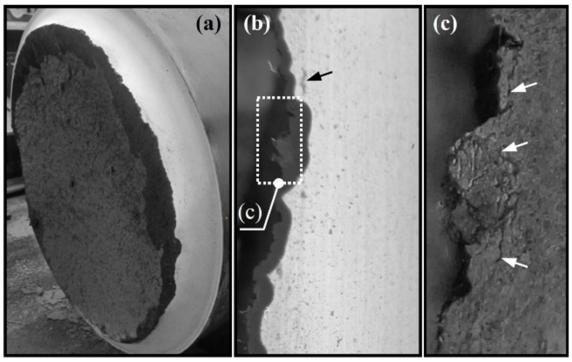

Fig.11. PT result of part A, (a) appearance, (b) cracks and micro-holes, and (c) defects near fracture surface.

Figure 12 (a) shows the PT results of the roll neck surface of Part B. Compared to Part A, the cracks and micro-holes at Part B can be found more easily and have more as shown in Figure 12 (b) and (c).

Those defects will increase the local stresses due to the stress concentration effect, and they also verified the inference above.

3.5 Discussion

The cracks detected by PT at Parts A and B are all developed in the circumferential direction. Those are perpendicular to the principal stress direction subjected to the roll force and have many micro-holes within or near the crack as shown in Figure 12 (b). It can be judged that these cracks were all induced by micro-holes while being subjected to roll force.

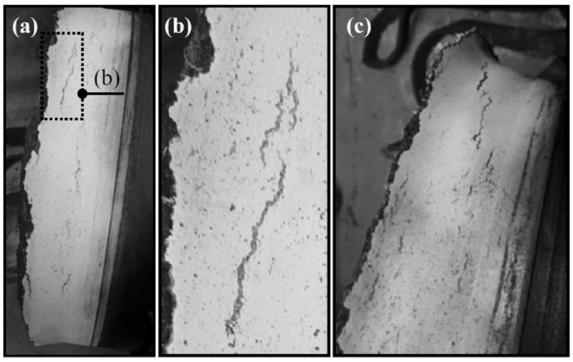

Fig.12. PT result of part B, (a) appearance, (b) cracks and micro-holes, and (c) defects at different locations.

The micro-holes were found around the whole circumference of the roll neck fillet. Zoomed in to observe the feature of the micro-holes, Figure 13 (a) near the fracture surface as an example, the boundary of the holes are irregular, without obvious burrs and scratches, which are different from the hole characteristics of casting porosity (Fig. 13 (b)) or invasion wear (Fig. 13 (c)). Its characteristics should belong to the pitting caused by corrosion.

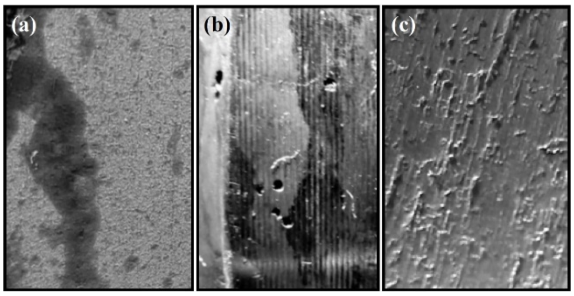

Fig.13. (a) The micro-holes around the roll neck, (b) Casting porosity, and (c) Abrasive wear.

Re-observed these pitting corrosions are mainly scattered within the area covered by the thrust ring, as shown in Figure 14 (a), which is one side press-fit on the backup roll shaft and the other side in close contact with the barrel end. The corrosion that occurred on the thrust ring press-fit region of the backup roll is more serious than the other surface, as shown in Figures 14 (b) and (c), and there is similar damage at the contact surface of the thrust ring (Fig. 14 (d)). It seems the presence of narrow gaps between the backup roll and the thrust ring gives rise to localized corrosion at these sites. These features match with crevice corrosion.

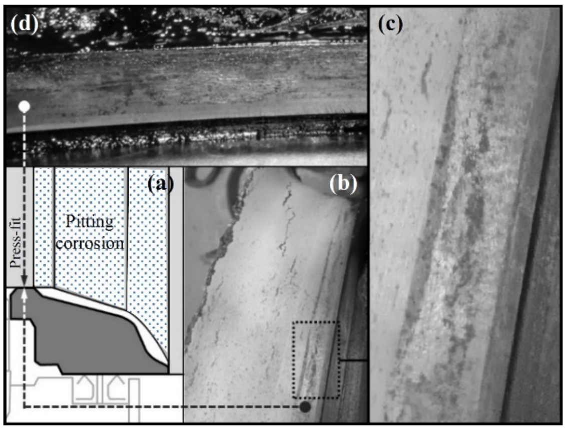

Fig.14. The pitting corrosion scattered region (a) and the crevice corrosion at the press-fit of the thrust ring (b) and the backup roll (c) (d).

Regardless of the material, a condition common to all types of crevice corrosion is the development of localized environments that may differ greatly from the bulk environment. In perhaps its simplest form, crevice corrosion may result from the establishment of oxygen differential cells. This can occur when oxygen within the crevice electrolyte is consumed, while the boldly exposed surface has ready access to oxygen and becomes cathodic relative to the crevice area(3).

Considering the above mechanism of crevice corrosion and the operating environment of this TNRL, it doesn't use cooling water or rolling oil during rolling, and the space between the thrust ring and backup roll is without any filling solution, it is inferred that the crevice corrosion between the thrust ring and the backup roll may have been caused by residues covering the gap in the past. Hence, there were residues on the thrust ring and its relative space of the backup roll as shown in Figure 15, which resulted in oxygen differential cells occurring in the local area. In addition, the corrosion was more served on the rough tooling marks region than on the fine region as shown in Figure 16.

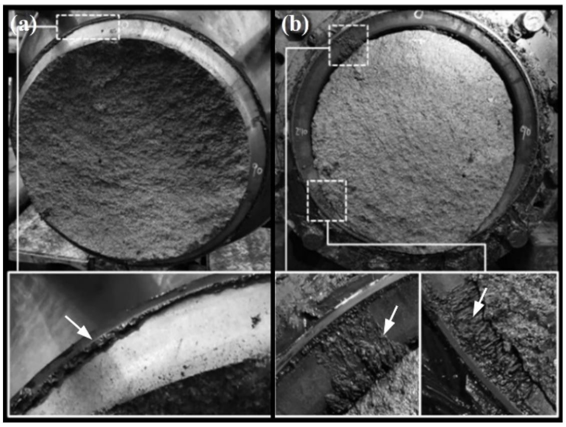

Fig.15. The residues at the thrust ring installation area of Part A (a) and Part B (b)

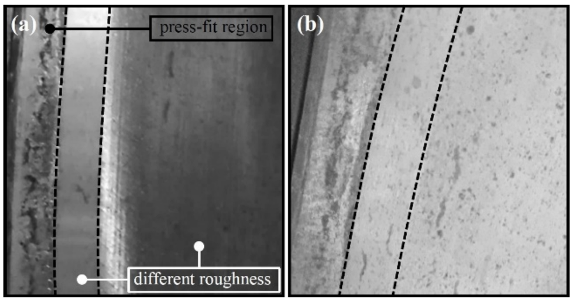

Fig.16. The corrosion at different roughness (a) VT results and (b) PT results.

Removing residues stuck in the gap after every campaign and upgrading the roughness of the fillet surface is recommended. It could effectively inhibit the corrosion development and might decelerate the crack propagation on the roll neck and prevent and/or terminate such roll failure in time to extend the life of mill rolls.

CONCLUSION

The 4-Hi rolling mill of a Temper and Recoil line is quite common to handle hot-rolled band coil. The top backup roll was broken around the drive-side roll neck during normal operation. After evaluating the stress of the roll, doing a detailed visual inspection of fractured parts, and a liquid penetration test (PT), we speculated that the root cause was the pitting at the fillet of the roll neck. These tiny pits could induce high-stress concentration at the fillet and form several circumferential cracks by rotating bending stress during the rolling process and then fracture eventually. The crevice corrosion between the backup roll and the thrust ring was inferred that induced the corrosive element to intrude the fillet. The obvious turning marks at the fillet also promoted a corrosion reaction. It is recommended to exclude such failure mechanisms by (1) Removing all residues that are stuck in the clearance between the backup roll and the thrust ring during every maintenance. (2) Upgrade the roughness of the fillet. Besides, inspect the fillet by PT more frequently, if there is already light corrosion in the fillet area, grind the tiny pits to decrease the opportunity for crack generation.

REFERENCES

1. W.T. Becker, S. Lampman: Fracture Appearance and Mechanisms of Deformation and Fracture, ASM Handbook V11.Failure Analysis and Prevention, 2002, pp. 559-586.
2. Russell A. Lund, Shahram Sheybany: Fatigue Fracture Appearances, ASM Handbook V11.Failure Analysis and Prevention, 2002, pp. 627-640.
3. Stephen C. Dexter: Localized Corrosion, ASM Handbook V13.Corrosion, 1987, pp. 238.