Finite Element Simulation and Multifactor Failure Analysis of an Important Stepped Shaft Fracture Events[1]

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Abstract: Aiming at a fracture event of an important stepped shaft parts, ABAQUS finite element method was used to simulate and analyze. The results show that the stress concentration is serious at the step where shaft fracture occurs. The maximum stress occurs at the R2 transition corner. The maximum stress value under the most unfavorable condition is 319.9MPa, which exceeds the yield strength limit of the material. Scanning Electron Microscope and X-ray Energy Spectrum analysis shows that fracture of the shaft is a fatigue fracture initiated by multiple sources. Design analysis states clearly that the initiation is mainly related to the small turning radius of the step, which causes the stress concentration factor increase. At the same time, the shoulder height is higher which cause the sudden change of the section size, and will aggravate the stress concentration effect. Furthermore, machining quality analysis indicates that the rough surface with micro-defects due to the out of control of metalworking may be the origin of fatigue crack initiation. Heat Treatment process quality analysis indicates that improper control of the quenching and tempering process has a negative impact on the initiation of the crack. Working conditions analysis shows that the actual load state, which exceeds the L2 intermediate level of the design standard load spectrum, is easy to accelerate the fatigue damage of mechanical parts.

Key words: stepped shaft parts; fatigue fracture; finite element; failure analysis

1. Event Overview

A 450t crane in a company, which has been in operation for 3 years, is used in large lifting operation. Due to the breakage of the drum shaft of the lifting mechanism, the lifting objects fall to the ground and the crane is damaged.

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Fig. 1 Drum Shaft of Lifting Mechanism of Crane

The fracture surface is located at the step of the stepped shaft. Macro morphology of the section is fatigue fracture and the final fracture zone is small (about Φ40mm).

Fig. 2 Macro-morphology of fracture surface

2. Structural and Force Analysis of Drum

The structure of the drum and the shaft is shown in Fig. 3. The fracture occurs at the turning angles of the steps of Φ180mm and Φ220mm of the shaft I, as indicated by the arrow.

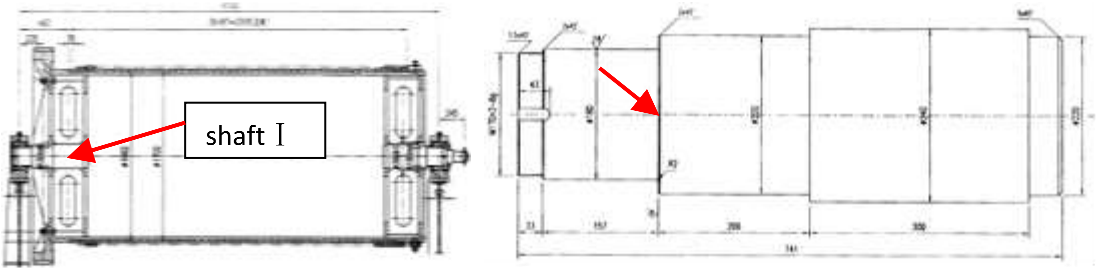

Fig. 3 Structural sketch of drum and shaft

According to the working conditions, the force analysis sketch of the drum structure is drawn as shown in Fig. 4, and the bearing support reaction of the drum shaft is solved. The results are shown in Table 1.

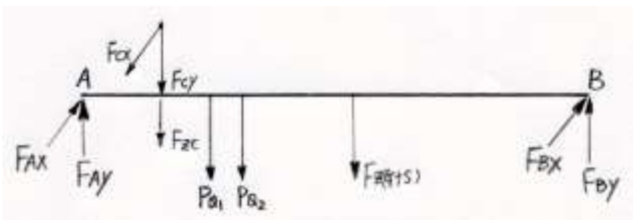

Fig. 4 Diagram of force analysis of drum structure

Table 1 Bearing Support Reaction on Drum Shaft

F_{AX}	F_{AY}	F_{BX}	F_{BY}
242.1KN	682.2KN	14.7KN	141.3KN

3. Finite Element Simulation

After checking correctly, the model is submitted to ABAQUS software for post-processing calculation, and the calculation results are shown in Figure 10.

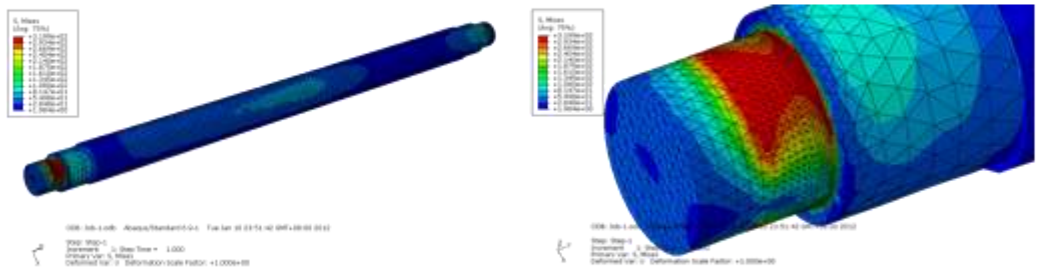

Fig. 10 Stress Distribution of the Shaft and Its Left End

From Figure 10, it can be seen that the stress concentration occurs at the fracture site of the shaft under rated load. The stress distribution phase diagram of its left end is analyzed. Maximum stress occurs at the transition point of R2 fillet. The maximum stress value is 319.9MPa, which exceeds the yield strength limit of the material Rel=315Mpa. In order to stereoscopically reflect the stress state of this section, the section is cut off along R2 rounded cross section, XY plane and YZ plane, and the stress distribution diagram is also shown in Figure 11.

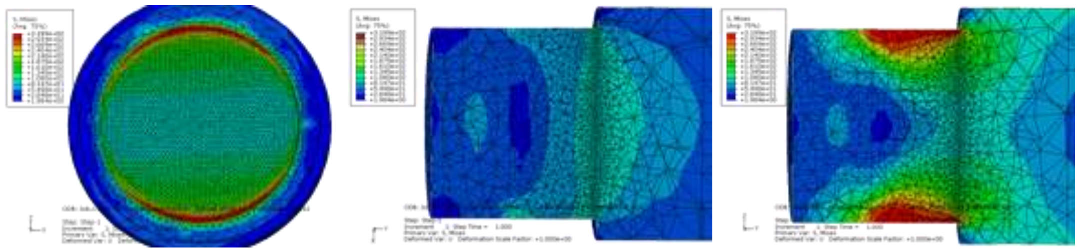

Fig. 11 Stress Distribution Diagrams of Cross Section, XY Section and YZ Section at R2 Round Corner at Axis Fracture

4. Failure Analysis

4.1 Design Analysis of Shaft

The design structure diagram shows that the radius of transition corner R=2mm at the step shaft Φ180mm / Φ220mm is less than the national standard value, and it is quite different from the industry standard value. If the radius of transition corner is too small, the stress concentration factor will increase. The shoulder height is higher which cause the sudden change of the section size, and will aggravate the stress concentration effect.

4.2 Quality Analysis of Heat Treatment Process

According to the technical requirements of the shaft (35 steel), the hardness after quenching and tempering should reach 170HB-200HB. Brinell hardness (Fig. 12) was measured from surface to interior on longitudinal of the shaft at Φ220mm fracture section. Physical and chemical test results show that the actual near surface hardness (220HB) exceeds the technical requirements, and the effective quenching layer depth is shallow, which has a certain impact on fatigue strength.

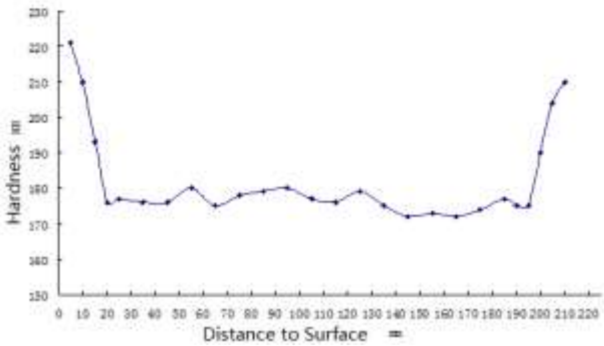

Fig. 12 Hardness gradient on longitudinal section of shaft at Φ220mm fracture zone

4.3 Quality Analysis of Metal Processing [6-7]

Compared with the roughness sample, the surface quality of the shaft is between 3.2μm and 6.3μm, and the roughness of the surface does not meet the design requirement of Ra1.6μm (Fig. 13). Surface state coefficient β has some influence on fatigue fracture, and surface micro-defects may be the origin of fatigue crack initiation.

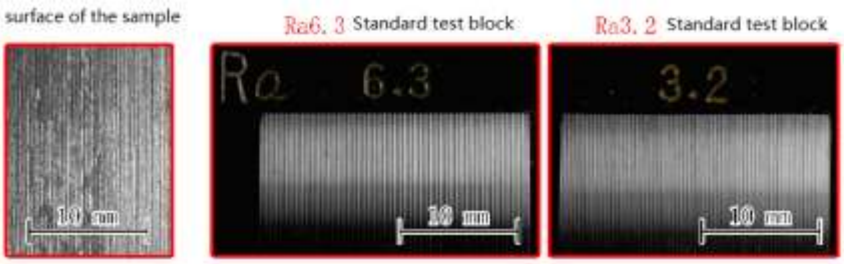

Fig.13 Comparisons of Surface Roughness in Turning

4.4 Scanning Electron Microscope and X-ray Energy Spectrum Analysis

The fatigue fracture of shafting can be clearly confirmed by scanning electron microscopy (SEM) analysis of the fracture surface of shafting (Fig.14). Parallel fatigue growth fringes and intergranular secondary cracks can be seen in the sub-edge region, showing brittle morphology.

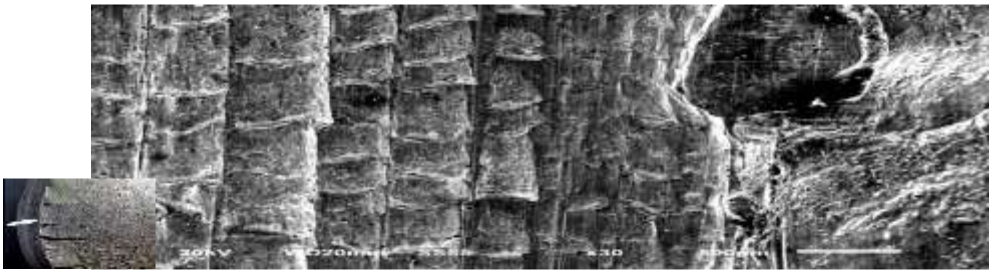

Fig. 14 Machining Traces of Rough Surface of Axis and Sub-layer Fatigue Glow

4.5 Working Conditions Analysis

Statistical data of hoisting mechanism operation show that the actual load state exceeds the L2-intermediate level of the design standard load spectrum, and it is easy to accelerate the fatigue damage of mechanical parts. At the same time, the fatigue fracture surface accounts for about 85% of the area of the cross-section, and the potential safety hazard cannot be found in daily use.

5. Conclusions

1. According to ABAQUS finite element simulation calculation, the maximum stress of local stress concentration exceeds the yield strength limit of material under the most unfavorable conditions at the transition corner of the shaft's Φ180 mm/ Φ220 mm step.

2. In the design of shaft, the selection of transition corner radius at fracture is too small and the selection of shoulder height is too large, which makes the stress concentration factor too high, and has adverse effects on the fatigue life of shaft.

3. The surface roughness and surface hardness of the fracture zone of the shaft do not meet the technical requirements, which will greatly reduce the toughness and fatigue resistance of the corner zone. The use beyond the design level has a negative impact on the initiation of cracking.

4. A large proportion of the fatigue growth zone on the cross section indicates that there is a period from crack initiation to final fracture, but the fatigue crack cannot be found in the daily maintenance of the crane during this period, which indicates that there is a blind area in the daily maintenance of the crane.

5. The fracture of the drum shaft is a fatigue fracture initiated by multiple sources. The initiation of the drum shaft is mainly related to the small transition fillet in the step area and the high stress concentration effect. It is easy to initiate fatigue cracking under impact load, which eventually leads to the overall failure, the drum losing its restraint, and high-speed rotation under the gravity drag of the suspender until the suspender falls to the ground and damaged.