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Fatigue fracture failure analysis of wind turbine blade root bolt

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Abstract

During fatigue testing of large-scale wind turbine blades, a common occurrence is the manifestation of fatigue fractures in the bolts located at the root of the blades. In-depth analysis of the bolt specimens undergoing fatigue testing involved macroscopic port analysis, chemical composition analysis, metallographic structure analysis, and electron microscope scanning. The findings reveal that fatigue fractures in the bolts result from the impact of cyclic alternating stress. Notably, stress concentration is conspicuous at the initial thread of the bolt, causing surface weakening and accelerating the initiation of fatigue crack origins. This, in turn, expedites the overall process of fatigue fracture.

Keywords

Wind turbine blade; High strength bolt; Fatigue crack; Failure analysis.

1. Introduction

Wind power generation, a pivotal facet of renewable energy, holds a crucial position in the global energy transition[1].Leveraging renewability and sustainability, wind power thrives on the widespread availability of domestic wind resources, propelling the rapid evolution of the wind power industry. Nevertheless, with turbine blades scaling unprecedented heights, incidents like blade fractures, spindle malfunctions, and bolt failures are on the rise. Consequently, concerns regarding the quality and safety of wind turbine units have gained widespread attention[2,3].

High-strength bolts hold a pivotal role in linking critical structural elements within wind turbine units, notably in locations like the tower, blade root, nacelle, and gearbox. Throughout blade operation, these bolts endure the impact of cyclic alternating loads, making them susceptible to fatigue and, in severe cases, fracture[4]. The M42 high-strength bolt, a vital component connecting turbine blades to the tower frame in large-scale wind turbine units, offers steadfast support to the entire blade system. Its quality directly influences the safety and performance of the entire wind turbine. During practical operation and fatigue testing of blades, recurrent fatigue fractures in blade root bolts are observed. This study conducts a thorough examination and analysis of the causes of bolt fractures, proposing corresponding remedial recommendations to eliminate defects and safety hazards stemming from bolt installation and operation, ensuring the secure and stable operation of the turbine unit[5].

2. Test and result

Examining the root bolts of a specific in-service model of wind turbine blades, we initiated a fatigue tensile test until fracture occurred. Following this, samples were obtained from the bolts through mechanical cutting. Using an OM metallographic microscope, EDS energy dispersive

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spectrometer, XRD, and SEM electron microscope, we conducted a comparative analysis on the chemical composition, phase, microstructure, and metallographic organization of both the fatigued and failed bolts.

2.1. Fracture analysis

2.1.1. Macroscope fractography

Analysis focused on three fatigued high-strength bolts. The first two bolts were fastened at both ends, secured by nuts, onto the fatigue testing machine. In contrast, the third bolt had one end secured by a nut, while the other was connected to a bolt sleeve. All the examined bolts were of the 10.9 grade, with fractures uniformly occurring at the base of the first thread. Figure 1 illustrates the macroscopic morphology of the front face of the fractured bolts, while Figure 2 showcases the macroscopic morphology of the fracture surface observed under an electron microscope.

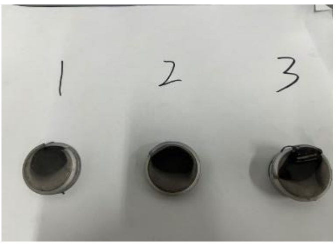

Fig. 1 Bolt cutting exterior appearance

Fig. 2 Electron microscope macroscopic view

Figure 1 reveals that the cross-sections of the first two sets of bolts are generally smooth with slight undulations, while the third set exhibits noticeable fracture protrusions. The fracture surface of the third set indicates three distinct regions: the crack initiation zone, propagation zone, and instantaneous fracture zone, discernible by directional patterns along the fracture. As depicted in Figure 2, the surface of the crack initiation zone displays a relatively smooth and stable concavity. It can be inferred that the original defect at the thread is the primary cause of stress concentration, acting as an external factor inducing crack initiation in the bolts.

2.1.2. Microscopic fracture analysis

Figure 3 provided image illustrates the scanning electron microscope's microscopic view of the bolt fracture surface. Clearly, the fracture aligns with high-cycle, multi-source fatigue failure, with the crack initiation point situated at the stress concentration zone near the bolt threads, highlighting the multifaceted nature of crack initiation.

A thorough analysis of the fracture surface and operational conditions leads to a preliminary assessment indicating that the root bolts are situated at the junction of the blade root and the pitch bearing[6]. Prolonged exposure to operational stress and alternating loads, particularly axial tensile stress, has led to fatigue-induced failure. Microcracks, concentrated due to stress, endure significantly higher stress levels than the average stress across the bolt section. Subjected to alternating loads, these microcracks propagate toward the core of the bolt, ultimately culminating in its fracture.

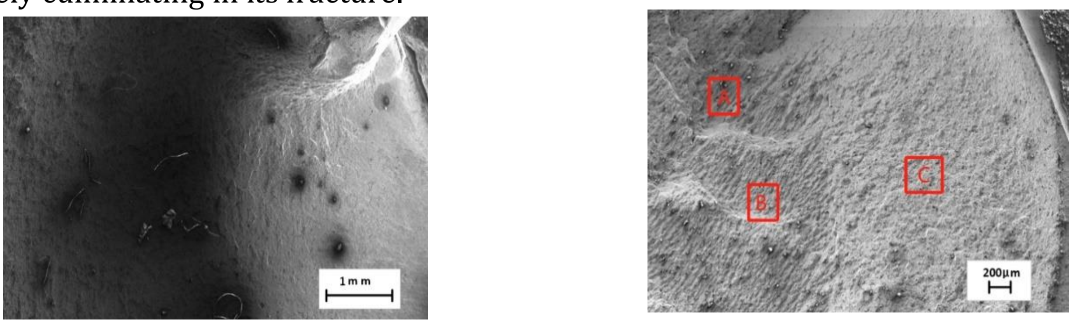

Fig. 3 Scanning electron microscope microscopic fracture morphology

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A, B, and C denote the fatigue fracture surface, fatigue initiation zone, and crack propagation zone, respectively. Notably, the crack originates from the edge region. Upon closer inspection in the magnified view, this region appears relatively smooth, displaying a deeper coloration. Under repetitive cycles of opening and closing, it experiences wear, progressively radiating radial streaks from the surface towards the interior.

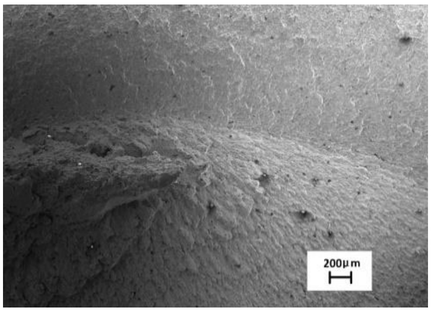

Fig. 4 Sectional extrusion ridges

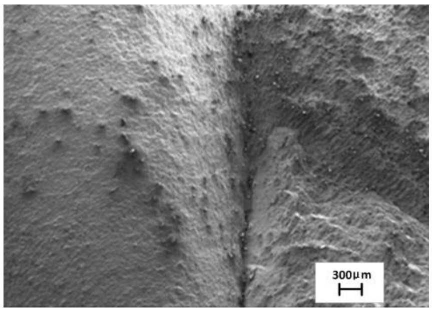

Fig. 5 Sectional intrusion grooves

Following the emergence of slip bands on the specimen's surface due to irreversible cyclic deformation, the fracture surface displays Figure 4 "extrusion ridges" and Figure 5 "intrusion grooves." These characteristics arise from uneven surface slipping of metal under the influence of alternating loads. The crack nucleation sites gradually expand and interconnect under the action of alternating stress, ultimately evolving into macroscopic fatigue cracks[7].

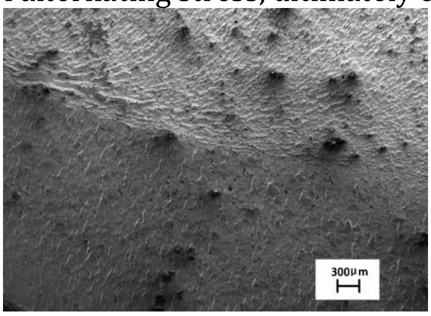

Fig. 6 Boundary between initiation zone and expansion zone

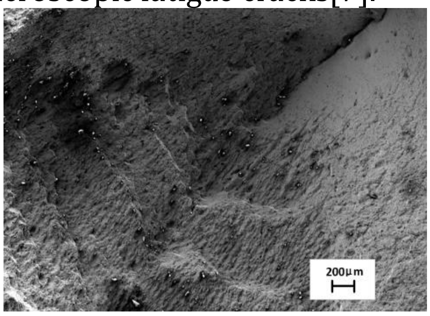

Fig. 7 Fatigue fracture step

Upon observing the region depicted in Figure 6, numerous fatigue arc lines are discernible, with cracks generally parallel and perpendicular to the direction of crack propagation, extending in the same direction as the secondary cracks. As cracks propagate and the material gradually undergoes deterioration, the remaining cross-section proves insufficient to withstand external loads, leading to rapid instability and the abrupt fracture of the specimen in the instantaneous failure zone. Bolt fractures result from the convergence of cracks expanding from different regions, forming a peak line upon intersection, thereby inducing fatigue fracture steps akin to those depicted in Figure 7.

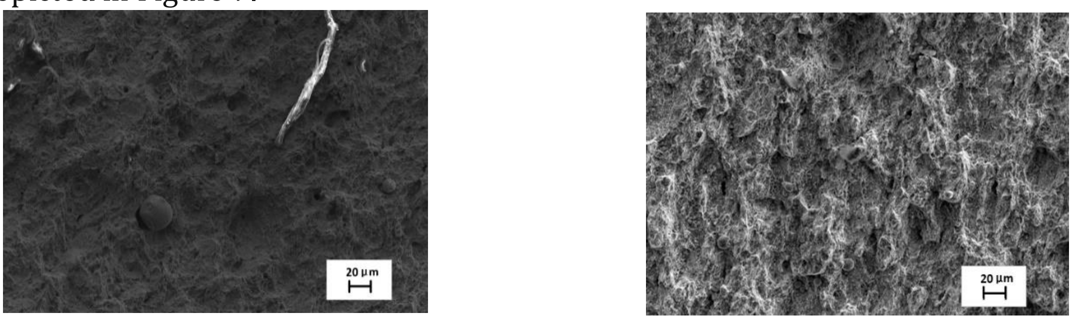

Fig. 8 Fracture impurity and dimple morphology

The crack originates at the thread root, as evident in Figure 8, progressing towards the thread core in a fatigued manner. The crack propagation zone exhibits fatigue striations, while the morphology in the instantaneous failure zone manifests as ductile dimples. The mechanism behind bolt fracture is fatigue failure, and on the fracture surface, there are discernible metal-like precipitates. Even after cleaning with an ultrasonic cleaning device before inspecting the fracture surface, these residues persist, indicating that impurities did not adhere to the bolt surface after the fracture occurred. This metallic impurity could also be one of the contributing factors to the initiation of the crack.

2.2. Metallographic structure analysis

The internal structure of the metal undergoes alterations in response to changes in external conditions or intrinsic factors. Through an analysis of the metallographic structure, one can assess whether there have been modifications in the organization and properties of the failed component. Image 9 illustrates the metallographic structures at locations distant from and proximate to the fracture site. The metallographic examination reveals that both the matrix structures near the fracture and those far from it consist of tempered martensite, with no apparent reticular formations observed at the grain boundaries, aligning with the prescribed standards for the metallurgical structure of this 40CrMoA material. It is evident from the image that the microstructures of both locations are relatively coarse, with the structure near the fracture exhibiting coarser characteristics compared to the structure away from the fracture.[8]

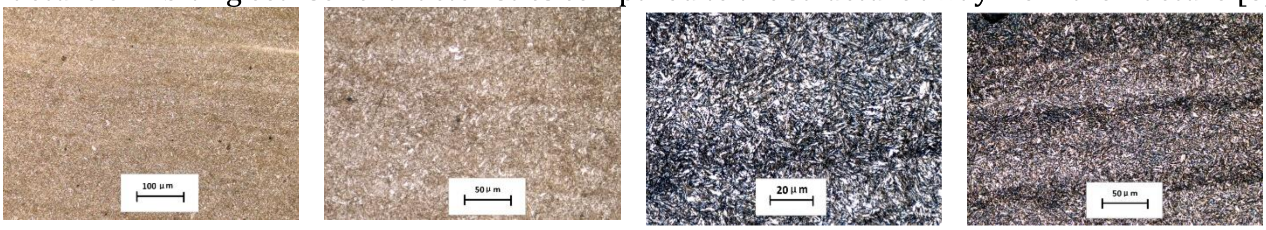

Fig. 9 Metallographic microstructure of fracture

The metallographic microstructure images of the bolt fracture surface reveal that the metallographic microstructure of the bolt matrix is tempered martensite. This suggests that the bolt has undergone quenching and high-temperature tempering treatments, resulting in excellent comprehensive mechanical properties. Notably, the presence of some ferrite in the image is observed. Ferrite, known for its low hardness and good plasticity, effectively strengthens the steel without compromising its plasticity and toughness, thereby optimizing the steel's performance.

2.3. Chemical composition analysis

For an in-depth examination of the chemical composition and distribution of corrosion products on the fracture surface, alongside a comparison of variations in chemical composition between the fracture surface and the core, an Energy Dispersive X-ray Spectroscopy (EDS) elemental analysis was carried out on both the fracture surface and the core. This analysis serves as an indirect method to understand the environment in which the failed component was situated, facilitating a subsequent analysis of the relationship between environmental factors and the occurrence of failure.

Table 1 EDS analysis of fracture surface

Element	P	S	Cr	Mn	Fe	Ni	Mo
D1	1.03	0.29	0.4	2.26	92.50	1.88	1.64
D2	0.26	0.39	1.05	2.09	92.16	1.47	2.58
D3	1.46	0.42	1.08	2.12	89.52	1.65	3.75

Table 1 reveals that the chemical composition of the fractured high-strength bolt primarily consists of four elements: Fe, Mn, Ni, and Mo. The minimal variance in elemental content indicates that there is negligible segregation of core components during the bolt's operational lifespan.

3. Analysis and discussion

The chemical composition of the bolt adheres to standard requirements, displaying minimal inclusions, a normal metallographic structure, and a fine grain size without discernible metallurgical or processing defects. Typically, the initial thread near the force application end of the bolt resides in a stress concentration zone. Insufficient strength in the bolt at this juncture poses a significant risk of fracturing, thereby presenting a latent threat to the assembly.

The fracture surface of the screw is perpendicular to the longitudinal axis, and the crack origin is situated on the surface, forming a flat fan-shaped area. The crack propagates along the grain boundaries, displaying characteristics of intergranular cracking in the initial expansion zone. Clearly visible are distinct, slightly curved fatigue striations resembling waves, accompanied by secondary cracks. Under electron microscopy, traces of crack extension from each cycle of alternating stress are clearly discernible, indicative of the typical features of fatigue fracture.[10]

The operational environment of wind turbine units is notably intricate, marked by frequent variations in wind conditions. This variability subjects the blade root bolts to alternating loads, with the thread root being the site of maximum stress concentration. In the presence of damage or impurities at this juncture, it is highly susceptible to serving as a crack initiation point. The gradual expansion of the crack origin under the influence of alternating loads ultimately culminates in bolt fracture. If the unit is situated in a coastal region, the probability of fatigue crack occurrence is further heightened.

4. Conclusion

Upon comprehensive analysis, it is discerned that the cause of bolt fracture is fatigue failure. Stress concentration at the threads results in lower strength and hardness of the bolt surface compared to the base material, accelerating the formation of fatigue crack origins. Furthermore, due to the alternating stress endured by the bolt, the accelerated expansion of the crack origins ultimately culminates in the fracture of the bolt.

The fracture nature of the bolt is fatigue failure, primarily attributed to stress concentration and the alternating loads borne by the bolt. The confirmation of the cracking cause in the wind turbine blade root connection bolts is substantiated by the aforementioned fracture surface morphology, metallographic analysis, and chemical composition analysis results. To enhance the fatigue life of the bolts, it is recommended to employ high-strength bolts of grade 12.9. Prior to mass deployment, a sampling inspection should be conducted to ensure the adequacy of the bolt's structure and performance.

Acknowledgements

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