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Enhancing Fatigue Life of Welded Joints in Wind Power Towers: A Comparative Study of Residual Stress Elimination Methods

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Abstract: ***This paper investigates welding-induced residual stresses in wind power towers and their critical influence on structural stability and fatigue strength. Various methods for mitigating welding residual stress and enhancing fatigue performance are examined. The study analyzes the underlying principles and effectiveness of key stress relief techniques, including heat treatment and vibration aging. In addition, approaches to improving fatigue strength—such as the optimization of welding processes and refinement of structural design—are elaborated. The findings are intended to serve as a reference for ensuring the reliable operation of wind power towers.***

Keywords: Wind Power Tower; Welding Stress Elimination; Fatigue Strength Improvement; Method Analysis.

1. INTRODUCTION

With the rapid development of the wind power industry, the quality and performance of wind power towers have become increasingly important. Welding stress can cause problems such as cracks and deformation of the tower, reduce its fatigue strength, and affect its service life. Therefore, in-depth analysis of the methods for eliminating welding stress and improving fatigue strength of wind power towers is of great significance for ensuring the safe and stable operation of wind power equipment.

2. OVERVIEW OF WELDING STRESS IN WIND POWER TOWER

2.1 Causes of Welding Stress

During the welding process of wind power tower drums, welding stress is generated due to various factors. First, uneven heating during welding is the main source of welding stress. When welding the tower drum, the weld area is rapidly heated while the surrounding areas remain at a relatively low temperature. This temperature difference leads to uneven thermal expansion of the material. The weld area expands significantly when heated but is restricted by the surrounding low-temperature areas and cannot expand freely, thus generating compressive stress; the surrounding areas, on the other hand, are pulled by the expansion of the weld, generating tensile stress. Second, differences in thermophysical properties between the welding material and the base metal can also cause stress. Different materials have different thermal expansion coefficients, thermal conductivities, etc., leading to inconsistent heat conduction and deformation behaviors during welding, which in turn generates stress. In addition, an unreasonable welding sequence can exacerbate stress generation. If the welding sequence is disorganized, stress will continue to accumulate and cannot be effectively released.

2.2 Classification of Welding Stress

Welding stress can be classified from different perspectives. According to the duration of the stress, it can be divided into transient stress and residual stress. Transient stress is generated during the welding process due to the effect of thermal cycles. As the welding process ends, part of the transient stress is released, but a portion remains in the welded part, forming residual stress. Residual stress is the focus of our attention, as it affects the long-term performance of the tower drum. According to the direction of stress action, welding stress can be divided into longitudinal stress, transverse stress, and thickness-direction stress. Longitudinal stress is the stress along the length of the tower drum's weld, mainly caused by longitudinal contraction of the weld; transverse stress is perpendicular to the length of the weld and is related to the transverse contraction of the weld and the interaction of longitudinal stress; thickness-direction stress is the stress in the wall thickness direction of the tower drum, which is relatively complex and related to factors such as uneven heat distribution in the wall thickness direction during welding and the layered structure of the material. In terms of stress nature, welding stress can be divided into tensile stress and compressive stress. Tensile stress tends to stretch the material, while compressive stress tends to compress it. In wind power tower drums, tensile stress is more likely to cause the initiation and propagation of cracks.

3. WELDING STRESS RELIEF METHODS

3.1 Principle and Application of Heat Treatment Method

Heat treatment is an important method to eliminate welding stress in wind power tower drums, and its principle is based on the thermal properties of materials. When heat treating the tower drum, the entire welded part or specific areas of the welded part are heated to a certain temperature and then slowly cooled. During the heating process, atoms inside the material gain sufficient energy, the bonding force between atoms changes, and the lattice structure is adjusted. For the welding area, this thermal effect can redistribute the originally uneven stress state caused by welding. The residual stress in the weld and its adjacent areas gradually relaxes during heating because at high temperatures, the yield strength of the material decreases, and parts originally in a high-stress state can adjust the stress distribution through local plastic deformation. During the cooling process, due to slow cooling, the material can shrink in a relatively uniform manner, thereby avoiding the generation of new stress. In terms of application, heat treatment requires determining appropriate heat treatment parameters based on factors such as the material, size, and welding process of the tower drum. For example, different steels have different phase transition temperatures, so the heating temperature must be strictly controlled within an appropriate range to ensure the effect of stress elimination without adversely affecting the material properties. Moreover, the heating rate and cooling rate also need to be carefully adjusted; excessively fast heating or cooling may cause new thermal stress inside the material.

3.2 Characteristics of Vibration Aging Method

Vibration aging is an efficient, energy-saving, and environmentally friendly method for eliminating welding stress. Its main feature is the use of vibrational energy to adjust the residual stress inside welded parts. When periodic vibrational loads are applied to wind turbine towers, the crystal structure inside the tower undergoes microscopic dislocation movement under the action of vibrational energy. This dislocation movement can promote the relaxation and redistribution of residual stress. Compared with heat treatment, vibration aging does not require heating and cooling of the welded parts, avoiding material structure changes and deformation problems that may be caused by the heating and cooling processes. It has the advantage of simple operation, as it does not require large heating equipment or complex cooling systems, only a suitable vibration aging device. Moreover, vibration aging can be performed in any working state of the welded part, whether it is a semi-finished product in the workshop or a tower already installed in a wind farm, as long as the vibration aging device can be installed and vibrational loads can be applied for stress elimination. In addition, the processing time of vibration aging is relatively short, which can quickly eliminate stress in welded parts and improve production efficiency. However, vibration aging also has certain limitations: its stress elimination effect may not be as thorough as that of heat treatment, especially for towers with high stress and complex structures, which may require multiple vibration aging treatments to achieve good results.

3.3 Operation of Mechanical Stretching Method

The mechanical stretching method is a technique to eliminate welding stress by applying external mechanical tensile force to wind turbine towers. The operation process first requires determining the appropriate tensile force based on the tower's dimensions, material properties, and welding conditions. This tensile force must not be too large, as it may exceed the material's yield limit and cause permanent deformation of the tower; nor should it be too small, otherwise, it cannot effectively eliminate welding stress. After determining the tensile force, specialized stretching equipment such as hydraulic stretchers is used to uniformly apply the tensile force to specific parts of the tower. Typically, the tensile force is applied along the weld direction because the weld is the main area of stress concentration. During the application of the tensile force, the welding stress inside the tower will redistribute as the material undergoes local stretching. The weld area originally in a high-stress state will gradually reduce stress after being subjected to external tensile force, and the material will undergo a certain degree of plastic deformation, thereby releasing the welding stress. During the stretching process, it is necessary to closely monitor the deformation of the tower to ensure that the stretching operation is carried out within a safe range. The advantages of the mechanical stretching method are that the equipment is relatively simple, the operation is intuitive, and it can target stress elimination for some areas with local stress concentration. However, it also has some shortcomings.

For example, for large-sized wind turbine towers, it is difficult to apply the tensile force uniformly, which may lead to uneven stress elimination effects.

4. APPROACHES TO IMPROVE FATIGUE STRENGTH

4.1 Optimization of Welding Process Parameters

Optimizing welding process parameters is crucial for improving the fatigue strength of wind turbine towers. Welding current, voltage, and welding speed are important welding process parameters. Reasonable adjustment of welding current can control the penetration depth and width of the weld. If the current is too high, it will lead to excessive weld penetration, which may cause overheating at the weld root, reduce the toughness of the weld, and thus affect the fatigue strength of the tower; conversely, if the current is too low, defects such as incomplete penetration may occur in the weld, which is also not conducive to improving fatigue strength. The welding voltage also needs to match the welding current; an appropriate voltage can ensure the stability of the arc and result in good weld formation. The welding speed directly affects the heat input of the weld. If the welding speed is too fast, the cooling rate of the weld will also accelerate, which may produce a hardened structure that is relatively brittle and prone to cracking under fatigue loads; while a too slow welding speed leads to excessive heat input, which will coarsen the weld grains and also reduce fatigue strength. In addition, the control of welding layers and interlayer temperature cannot be ignored. A reasonable number of welding layers can ensure the quality of the weld. Excessively high or low interlayer temperatures will affect the performance of the weld, and an appropriate interlayer temperature helps to refine the weld grains and improve fatigue strength.

4.2 Improving Welded Joint Design

Improving welded joint design is one of the effective ways to enhance the fatigue strength of wind turbine towers. When designing welded joints, the form of the joint should first be considered. For example, butt joints have better performance than fillet joints when subjected to fatigue loads. This is because butt joints allow stress to be evenly distributed at the weld, reducing stress concentration. At the same time, the groove form of butt joints also needs careful design. Appropriate groove forms, such as V-grooves and U-grooves, can not only ensure weld penetration but also reduce heat input during welding, thereby improving weld performance. In addition, adding transition fillets at welded joints is a common design method. Transition fillets can effectively reduce the stress concentration factor; when fatigue loads act on the tower, stress can transition smoothly at the fillets, avoiding stress concentration at sharp corners. Furthermore, in joint design, structures such as reinforcing plates can be considered to improve the load-bearing capacity of the joint, but care must be taken that the design of the reinforcing plates does not introduce new stress concentration points.

4.3 Adopting Surface Strengthening Treatment

Surface strengthening treatment can significantly improve the fatigue strength of wind turbine towers. Common surface strengthening methods include shot peening, rolling, etc. Shot peening uses high-speed projectiles to impact the tower surface, causing plastic deformation. This plastic deformation forms a residual compressive stress layer on the surface. Under fatigue loading, the residual compressive stress can offset part of the tensile stress, thereby improving the fatigue strength of the tower. Because during the fatigue process, tensile stress is the main factor leading to the initiation and propagation of cracks, and the existence of residual compressive stress can effectively inhibit the initiation of cracks. Rolling treatment involves rolling the tower surface with rolling tools, causing plastic flow of the surface material, which also forms a residual compressive stress layer. Moreover, rolling treatment can also refine the surface material, improving surface hardness and wear resistance. The effect of surface strengthening treatment is closely related to processing parameters, such as shot peening projectile diameter, speed, jet angle, as well as rolling pressure, rolling times, etc. Different tower materials and structures may require different processing parameters to achieve the best strengthening effect.

5. EFFECT EVALUATION OF THE METHOD

5.1 Detection of Stress Relief Effect

Detecting the welding stress relief effect of wind turbine towers is crucial for ensuring tower quality. Common detection methods include X-ray diffraction, magnetic measurement, etc. X-ray diffraction is based on the principle of X-ray diffraction by crystalline materials. When X rays irradiate the tower material, different stress states will cause changes in the crystal lattice spacing, thereby changing the position and intensity of the X ray diffraction peaks. By measuring these changes in the diffraction peaks, the internal stress of the material can be calculated. This method has the advantage of high precision and can accurately detect the residual stress inside the material, but the equipment is expensive, the operation is complex, and professional technicians are required. Magnetic measurement uses the relationship between the magnetism of the material and stress to detect stress. When the material is under stress, its magnetic permeability changes, and the stress is inferred by measuring the change in magnetic permeability. Magnetic measurement is relatively easy to operate and has lower equipment costs, but its detection accuracy is relatively lower than that of X ray diffraction. In practical applications, an appropriate detection method can be selected according to specific circumstances, or the two methods can be used in combination to more comprehensively and accurately evaluate the effect of stress relief.

5.2 Measurement of Fatigue Strength Improvement

Evaluating the improvement of fatigue strength in wind turbine towers is a complex process. First, it can be directly assessed through fatigue testing. Fatigue testing simulates the fatigue load conditions that the tower experiences during actual use, applying multiple cyclic loads to the treated tower specimens until failure occurs. By comparing the number of cyclic loads the specimens can withstand before and after treatment, the improvement in fatigue strength can be intuitively understood. For example, if the treated tower specimen can withstand a certain number more cyclic loads than before treatment, it indicates an improvement in fatigue strength. Additionally, theoretical calculations can be used to evaluate the improvement in fatigue strength. Based on factors such as material mechanical properties, welded joint design, and stress state, fatigue strength calculation models, such as the Goodman diagram, are used to compute the theoretical fatigue strength values of the tower before and after treatment, which are then compared. However, theoretical calculations often require certain assumptions and may have some deviations from actual conditions, so they need to be combined with fatigue test results to comprehensively evaluate the improvement in fatigue strength.

5.3 Comparative Analysis of Different Methods

A comparative analysis of different methods for welding stress relief and fatigue strength improvement of wind turbine towers helps in selecting the most suitable method. In terms of stress relief effectiveness, heat treatment generally achieves a more thorough stress relief effect, especially for towers with high stress and complex structures. Although vibration aging is easy to operate, energy-efficient, and environmentally friendly, its stress relief effect is slightly inferior to that of heat treatment. Mechanical stretching has a good effect on relieving local stress concentration areas but has limited effect on overall stress relief. In terms of improving fatigue strength, optimizing welding process parameters, improving welded joint design, and adopting surface strengthening treatment each have their own advantages. Optimizing welding process parameters starts from the welding process, directly affecting weld quality and thereby improving fatigue strength; improving welded joint design mainly reduces stress concentration through structural optimization to enhance fatigue strength; surface strengthening treatment forms a residual compressive stress layer on the tower surface to resist fatigue loads. Different methods also differ in cost, operational difficulty, and application scope. Heat treatment has a higher cost, requiring specialized equipment and Venue, with strict operational requirements; vibration aging has lower cost and simple operation but may require multiple treatments; mechanical stretching has simple equipment but requires accurate control of tensile force during operation.

6. CONCLUSION

In summary, through the analysis of methods for eliminating welding stress and improving fatigue strength of wind power tower drums, various effective means have been identified. Reasonable application of these methods can significantly reduce welding stress and enhance fatigue strength. Future research needs to be further deepened, optimizing methods in combination with actual demands to promote the continuous progress of wind power tower drum manufacturing technology.

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