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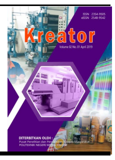

Non-Destructive Evaluation of Circumferential Welds in Wind Turbine Tower Shells Using Magnetic Particle Testing

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ABSTRAK

Pengelasan merupakan salah satu proses penting dalam fabrikasi struktur menara turbin angin, khususnya pada sambungan circumferential weld pada bagian shell. Kualitas sambungan las sangat menentukan kekuatan struktur dan keandalan operasional turbin angin. Penelitian ini bertujuan untuk mendeteksi cacat pengelasan pada sambungan circumferential weld pada shell tower turbin angin menggunakan metode Magnetic Particle Testing (MPT). Metode pengujian yang digunakan adalah MPT tipe wet visible, yang termasuk dalam metode non-destructive testing untuk mengidentifikasi cacat permukaan dan cacat dekat permukaan pada material ferromagnetik. Proses pengujian dilakukan pada satu sambungan las circumferential pada shell menara turbin angin. Hasil inspeksi menunjukkan adanya beberapa indikasi cacat pada area pengelasan, yaitu retak, porositas, dan inklusi terak. Keberadaan cacat-cacat tersebut berpotensi menurunkan kualitas dan kekuatan sambungan las pada struktur menara turbin angin, sehingga diperlukan tindakan perbaikan pada area pengelasan yang terindikasi cacat guna memastikan integritas struktur dan mencegah potensi kegagalan pada komponen. Penelitian ini menunjukkan bahwa metode Magnetic Particle Testing efektif digunakan sebagai teknik inspeksi awal untuk mendeteksi cacat pada sambungan las struktur menara turbin angin

ABSTRACT

Welding is one of the most important processes in the fabrication of wind turbine tower structures, particularly in the circumferential weld joints of the shell section. The quality of the welded joint greatly determines the structural strength and operational reliability of wind turbines. This study aims to detect welding defects in circumferential weld joints of wind turbine tower shells using the Magnetic Particle Testing (MPT) method. The testing method employed is the wet visible type of MPT, which is a non-destructive testing technique used to identify surface and near-surface defects in ferromagnetic materials. The inspection process was conducted on a circumferential weld joint on a wind turbine tower shell. The inspection results revealed several indications of welding defects in the weld area, including cracks, porosity, and slag inclusions. The presence of these defects has the potential to reduce the quality and strength of the welded joint in the wind turbine tower structure.

1. INTRODUCTION

The global transition toward renewable energy has significantly increased the development and deployment of wind power systems (Bensalah et al., 2022; Bošnjakovic et al., 2022). Wind turbines have become one of the most important technologies for sustainable electricity generation due to their ability to convert wind energy into electrical energy efficiently (Hossain et al., 2013). As wind turbines continue to grow in size and capacity, the structural reliability of their supporting components becomes increasingly critical. One of the key structural components is the wind turbine

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tower, which supports the nacelle and rotor and must withstand various loads, including wind loads, dynamic forces, and cyclic stresses during operation (Hernandez-Estrada et al., 2021).

Wind turbine towers are typically constructed from large cylindrical steel shells that are connected through circumferential welding. The welded joints play a vital role in maintaining the structural integrity and stability of the tower. However, welding processes may introduce various discontinuities or defects such as cracks, porosity, slag inclusions, and lack of fusion (Arandjelovic et al., 2024; Thomas, 2018). These defects can reduce the mechanical strength of the welded joints and may become critical points that initiate structural failure under operational loading conditions. Therefore, ensuring the quality of welded joints during fabrication is essential to guarantee the safety and durability of wind turbine structures.

To maintain weld quality, inspection and quality control procedures are required to detect possible defects in welded structures. Non-Destructive Testing (NDT) techniques are widely applied in industrial inspection because they allow the detection of defects without damaging the inspected component. Several NDT methods are commonly used in weld inspection, including ultrasonic testing, radiographic testing, dye penetrant testing, and magnetic particle testing (Gupta et al., 2022; Kumar & Mahto, 2013). Among these methods, Magnetic Particle Testing (MPT) is widely used for detecting surface and near-surface defects in ferromagnetic materials due to its relatively simple procedure, high sensitivity to small discontinuities, and rapid inspection capability (Deepak et al., 2021).

Magnetic Particle Testing works by magnetizing the test material and applying ferromagnetic particles to the surface. When a discontinuity such as a crack or inclusion is present, the magnetic flux leakage occurs around the defect area, causing the magnetic particles to accumulate and form a visible indication. The wet visible method of MPT is often used in industrial applications because it provides good particle mobility and improved defect indication visibility.

Based on these considerations, this study focuses on the inspection of circumferential weld joints on a wind turbine tower shell using the Magnetic Particle Testing method with a wet visible technique. The objective of this research is to detect and identify welding defects present in the welded joint and to evaluate the condition of the weld based on the inspection results. The results of this study are expected to contribute to the understanding of weld quality in wind turbine tower fabrication and support quality control efforts in welded structural components.

2. METHOD

This study employed a non-destructive testing (NDT) method to detect welding defects in circumferential weld joints of a wind turbine tower shell. The inspection was conducted using wet Magnetic Particle Testing (MPT) with an AC yoke (4.5 kg lifting force) and a magnetization level of approximately 4 kA/m, enabling detection of fine surface-breaking defects. The procedure was performed by certified personnel in accordance with ISO 9712:2022 to ensure reliability; however, no comparative validation was conducted, and thus detection accuracy depends on the inspection procedure and operator expertise. The object of this research was a circumferential weld joint on a wind turbine tower shell structure. The inspection was limited to a single circumferential weld area. This approach was intended as a preliminary case study to assess the effectiveness of Magnetic Particle Testing in detecting surface defects. However, it may not fully represent the variability of weld quality across the entire tower structure.

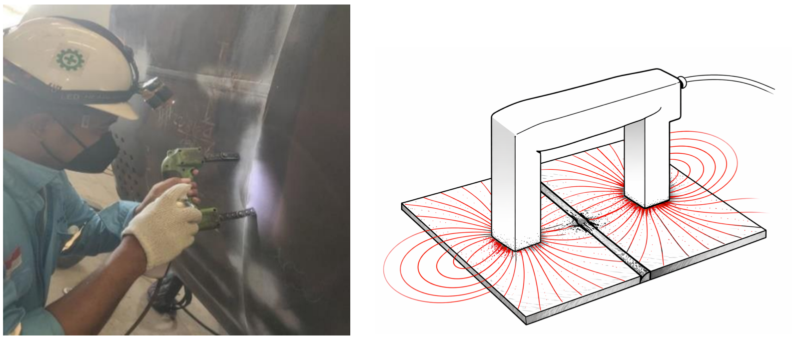
Before testing, the weld surface was cleaned to remove contaminants such as oil, dust, and welding residues. Then, WCP-2 white contrast paint applied at surface test area to enhance the visibility of magnetic particle indications. Subsequently, 7HF magnetic particles, consisting of fine ferromagnetic particles suspended in a liquid carrier, were applied to the surface. Magnetization of the inspection area was carried out using a Magnaflux magnetic yoke with a lifting capacity of 4.5 kg. The presence of discontinuities was indicated by the accumulation of magnetic particles along the magnetic flux leakage fields at defect locations, which were then visually evaluated.

If a discontinuity exists, magnetic flux leakage occurs and the particles accumulate at the defect location, forming visible indications. The observed indications were visually examined and recorded. The patterns of particle accumulation were then interpreted to identify the types of welding defects present in the circumferential weld area. The inspection results were used to evaluate the weld condition and determine the need for corrective action.

3. RESULT AND DISCUSSION

Magnetic Particle Testing Procedure

Non-Destructive Testing (NDT) using Magnetic Particle Testing (MPT) was performed after the completion of the welding process on the circumferential joint of the wind turbine tower shell. The inspection was carried out at the manufacturing site using a portable magnetic yoke, following the procedures recommended in ASTM E709 and ASME Section V for magnetic particle examination. Prior to inspection, the weld surface was cleaned and coated with WCP-2 white contrast paint to enhance the visibility of magnetic particle indications. During the inspection, the operator carefully positioned the magnetic yoke as illustrated in Figure 1.b to generate a magnetic field across the welded area. The magnetization process was applied in two stages to ensure reliable defect detection. In the first stage, the magnetic field was oriented at an angle of 30–40° relative to the weld axis, as shown in Figure 1.a. In the second stage, the magnetic field was applied perpendicular (90°) to the weld axis. The use of two magnetization directions was intended to improve inspection reliability, as discontinuities with different orientations can be more effectively detected when the magnetic field is applied in multiple directions.



(a) (b)

Figure 1. Magnetic Particle Testing (MPT) inspection of a welded joint: **(a)** weld quality inspection conducted by an operator; **(b)** schematic representation of the magnetic field distribution during MPT inspection

Inspection Results

The inspection of the welded joints identified several discontinuities, as shown in Figures 2–7. Through visual observation supported by Magnetic Particle Testing (MPT), the detected indications were categorized into surface and subsurface defects. The observed defect sizes ranged from 3 to 11 mm, exceeding the acceptance criterion of ≤ 1.5 mm. Surface defects generally appeared as well-defined linear indications with moderate to strong intensity, while subsurface defects exhibited more diffuse and lower-intensity patterns. Surface defects are presented in Figures 2–4, while Figures 5–7 illustrate indications of subsurface discontinuities detected during the inspection process.

Figure 2. Surface cluster porosity

Figure 2 shows a porosity defect located on the weld surface. This defect is characterized by the presence of small clustered cavities formed due to trapped gas during the solidification of the molten metal. Such defects commonly occur when gas is unable to escape from the weld pool during the welding process.

Figure 3. Slag inclusion

Figure 3 presents a slag inclusion defect, which occurs when non-metallic slag becomes trapped within the molten weld metal. After the cleaning process, the defect appears as small cavities or irregular openings on the weld surface.

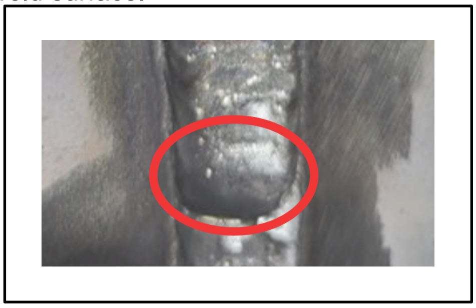


Figure 4. Overlap

Figure 4 illustrates an overlap defect, which is identified by the accumulation of weld metal that flows onto the base metal without proper fusion. This defect generally occurs due to improper welding parameters, such as excessive welding speed, low heat input, or improper electrode manipulation.

The presence of these defects indicates that the welding process parameters and operational control play an important role in determining the final weld quality. Therefore, proper parameter selection and welding technique are essential to minimize the occurrence of discontinuities in welded structures.

Meanwhile, other observations indicate the presence of subsurface defects, which are identified by the accumulation of magnetic particles on the inspected surface. The accumulation of particles forming a linear indication suggests the presence of a subsurface crack, as shown in Figure 5. In addition, black spot indications observed during the inspection represent the presence of **voids** beneath the surface, as shown in Figure 6. These indications appear due to magnetic flux leakage caused by discontinuities within the material, allowing the magnetic particles to accumulate and form visible patterns on the inspected area.

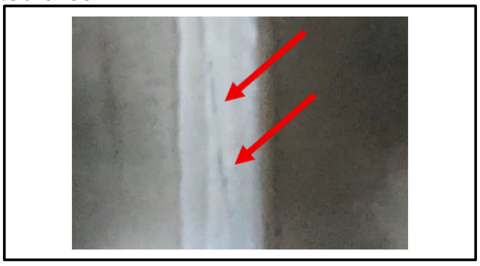


Figure 5. Crack

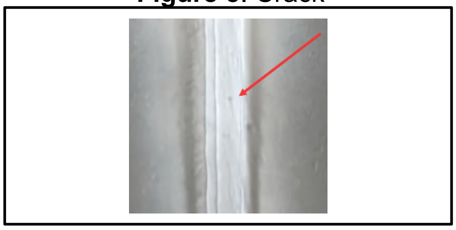


Figure 6. porosity

Discussion

The inspection results indicate the presence of several welding defects detected through Magnetic Particle Testing (MPT), including porosity, slag inclusion, overlap, cracks, and voids. These defects were identified through the accumulation patterns of magnetic particles formed due to magnetic flux leakage when the magnetic field encountered discontinuities within the welded material. The ability of MPT to reveal both surface and near-surface defects demonstrates its effectiveness as a non-destructive testing method for evaluating weld quality in ferromagnetic structures.

The presence of porosity defects, as observed in Figure 2, is generally associated with gas entrapment during the solidification of molten metal. This condition may occur due to contamination, improper shielding gas protection, or excessive moisture in the electrode or base material. Meanwhile, slag inclusion defects indicate that non-metallic slag was trapped in the weld metal, which may result from insufficient cleaning between welding passes or improper welding techniques.

The overlap defect observed in the inspection suggests that the weld metal flowed onto the base metal without achieving proper fusion. This condition is commonly related to improper welding parameters, such as excessive welding speed, low heat input, or incorrect electrode angle during the welding process. In addition, the identification of linear indications and rounded indications during the inspection suggests the presence of subsurface cracks and voids, which may originate from thermal stresses, rapid cooling, or internal material discontinuities.

These findings highlight the importance of proper control of welding parameters and operational procedures during the fabrication process. In large welded structures such as wind turbine towers, weld integrity plays a crucial role in maintaining structural reliability under cyclic loading conditions. Therefore, the application of MPT as part of quality control procedures is essential to ensure the structural safety and performance of welded components.

The findings of this study are consistent with previous research on the application of Magnetic Particle Testing (MPT) for the detection of welding defects in ferromagnetic materials. Several studies have reported that MPT is highly effective in identifying surface and near-surface discontinuities, including porosity, cracks, slag inclusion, and other welding imperfections. These defects generate magnetic flux leakage, which allows magnetic particles to accumulate and form visible indications on the inspected surface.

Previous investigations have also demonstrated that the orientation of the applied magnetic field plays an important role in defect detection. Applying the magnetic field in multiple directions increases the probability of detecting discontinuities with different orientations. This principle is consistent with the procedure applied in this study, where the magnetic field was applied at an angle of 30–40° relative to the weld axis and subsequently perpendicular (90°) to the weld axis. Such a two-directional magnetization approach improves the reliability of defect detection.

Furthermore, similar welding defects such as porosity, slag inclusion, and overlap have been reported in welded structures when welding parameters are not properly controlled. Factors such as welding speed, heat input, electrode manipulation, and insufficient cleaning between welding passes are commonly associated with the formation of these defects. Therefore, the results obtained in this study support previous findings regarding the relationship between welding process parameters and the occurrence of weld discontinuities.

4. CONCLUSION

Based on the inspection results using Magnetic Particle Testing (MPT) on the welded joints of the wind turbine tower structure, it can be concluded that the inspection successfully detected both surface and subsurface discontinuities. The identified surface defects include porosity, slag inclusion, and overlap, which became clearly visible after the cleaning process of the weld surface. In addition, subsurface discontinuities were indicated by the accumulation patterns of magnetic particles, forming linear and rounded indications that suggest the presence of cracks and voids beneath the surface. The application of the magnetic field in two different orientations, namely 30–40° and 90° relative to the weld axis, improved the reliability of defect detection because discontinuities with different orientations could be identified more effectively. The occurrence of these defects indicates that welding parameters and process control play an important role in determining the quality of welded joints. Therefore, the implementation of Magnetic Particle Testing as part of the non-destructive evaluation process is essential to ensure the structural integrity and reliability of welded components in large-scale structures such as wind turbine towers.

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