



Failure Mechanism Analysis of 253MA Vortex Finder in A CFB Boiler Under High-Temperature Erosion and Refractory Deposit Exposure

**Martua Haposan Echo
Sihite***

Universitas Gadjah Mada,
Indonesia

Kusmono

Universitas Gadjah Mada,
Indonesia

***Corresponding author:**

Martua Haposan Echo Sihite, Universitas Gadjah Mada, Indonesia.

✉ martuahaposanechosihite@mail.ugm.ac.id

Article Info:

Article history:

Received: May 13, 2026

Revised: June 24, 2026

Accepted: July 08, 2026

Keywords:

Vortex Finder; Material Failure;
Hotspot; SEM-EDS; CFB Boiler;
XRD.

Abstract

Background: Circulating fluidized bed (CFB) boilers are widely applied in coal-fired power plants due to their fuel flexibility and low emissions. The vortex finder, a key cyclone component, separates solid particles from flue gas and is prone to wear under high-temperature, erosive conditions. **Objective:** This study aims to identify failure characteristics, analyze the causes, and explain the failure mechanism of a 253MA vortex finder in a 2 × 100 MW CFB boiler at PLTU Sebalang after 6,548 operating hours at 850–950°C.

Methods: A multi-method approach was employed, including visual inspection, positive material identification (PMI), tensile testing, microhardness testing, optical microscopy, scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS), and X-ray diffraction (XRD) analysis to assess mechanical and microstructural degradation.

Results: The vortex finder exhibited plastic deformation, material thinning, and deposition of foreign refractory material. Tensile strength decreased from 723.89 MPa to 677.84 MPa (6.36%), elongation decreased from 58% to 53%, and hardness decreased from 218.84 HV to 210.21 HV. Microstructural changes included grain coarsening and carbide precipitation, while SEM-EDS revealed surface roughening, early microcrack initiation, and compositional changes indicative of high-temperature oxidation. XRD confirmed that the deposits consisted of alumina–silica refractory material.

Conclusion: Failure resulted from a synergistic mechanism involving high-velocity particle erosion, refractory deposit accumulation, and progressive microstructural degradation. Crack initiation and propagation ultimately led to structural failure. Recommendations include implementing erosion control measures, maintaining refractory linings, applying more erosion-resistant coatings or alternative materials, and adopting condition-based inspection strategies to enhance component reliability.

To cite this article: Sihite, M. H. E., & Kusmono. (2026). Failure Mechanism Analysis of 253MA Vortex Finder in A CFB Boiler Under High-Temperature Erosion and Refractory Deposit Exposure. *Equivalent: Jurnal Ilmiah Sosial Teknik*, 8(3), 850-866. <https://doi.org/10.59261/jequi.v8i3.342>

INTRODUCTION

The demand for electrical energy in Indonesia continues to increase in line with economic growth, industrialization, and population growth (Jamilatun et al., 2025). According to data from the Ministry of Energy and Mineral Resources (2022), national electricity consumption is projected to grow by an average of 4.9% per year over the next decade, requiring the provision of reliable, efficient, and sustainable electrical energy. In this context, steam power plants (PLTU) remain the backbone of the national electricity supply, contributing more than 60% of the total

installed capacity of Indonesia's electricity system (Negara, 2024). Therefore, the operational reliability of steam power plants is a strategic factor in ensuring continuity of electricity supply (Baskoro & Wardhana, 2026).

The reliability of electricity supply is highly dependent on the performance and availability of generating units (Darmawan & Wibowo, 2024; Mawuntu et al., 2024). Any disturbance or failure of major components in the power generation system may cause a forced outage, reducing system reliability and increasing operational and maintenance costs (MAULANA, 2026; Pamungkas et al., 2021). In a Circulating Fluidized Bed (CFB)-based steam power plant system, one critical component that determines combustion efficiency and particle separation is the boiler cyclone. The reliability of the boiler cyclone is essential because this component functions to separate solid particles from the hot flue gas stream before the gas is directed to the next heat exchanger (Basu, 2006; Malik, 2024). Inside the cyclone, the vortex finder plays a vital role in regulating fluid flow and maintaining the stability of the high-temperature gas vortex (Yohana et al., 2023). Degradation or damage to the vortex finder may reduce particle separation efficiency, increase ash carryover, and even create the potential for further damage to the superheater or economizer due to abrasion.

Previous studies have shown that the vortex finder is one of the most vulnerable points to material degradation in CFB systems operating at high temperatures (Facheruddin, 2023). Hagman et al. (2019) reported that in a biomass co-firing application, a vortex finder operating at 880 °C experienced alloy degradation due to a combination of corrosion, oxidation, and sulfidation mechanisms. This process is aggravated by turbulent conditions, solid-particle impingement, and extreme thermal fluctuations inside the cyclone (Dagdag et al., 2025). Meanwhile, Arjunwadkar et al. (2016), in their review of CFB boiler operation and maintenance issues, emphasized that material failure in cyclone components is often caused by suboptimal design, inappropriate material selection for combustion conditions, and fouling due to ash accumulation, which accelerates thermal and mechanical degradation (Konist, 2023). However, a significant research gap exists in the current literature. While studies on high-temperature alloy degradation have been conducted in laboratory settings (Alviana et al., 2023) and on other boiler components such as superheater tubes (Facheruddin, 2023; Triasdian et al., 2021), comprehensive failure analysis specifically targeting vortex finders made of 253MA under actual CFB operating conditions remains limited. Moreover, existing studies predominantly originate from European and North American contexts (Dagdag et al., 2025; Hagman et al., 2019), with limited investigation of CFB boiler component failures in tropical operating environments such as Indonesia, where coal characteristics, ambient conditions, and maintenance practices may differ substantially. This study addresses this gap by providing a systematic, multi-method failure analysis of a 253MA vortex finder that operated under real industrial conditions in an Indonesian CFB power plant.

This condition was also observed in one vortex finder unit of the CFB boiler cyclone in the 2 × 100 MW steam power plant that is the object of this study. The vortex finder is installed inside the boiler cyclone. This area shows a configuration of several material layers, namely corundum pouring with a thickness of approximately 70 mm, common pouring with a thickness of approximately 90 mm, and insulation layers consisting of silicate fiber felt and plywood, each approximately 20 mm thick. The main structural dimensions indicate an inner diameter of approximately Ø2560 mm, with a base support element 535 mm wide.

During the boiler inspection on January 13, 2025, indications of failure were found in the form of deformation at the end of the vortex finder, as shown in Figure 1. This material failure occurred in segment 1, or the uppermost segment of the vortex finder. During the visual inspection of the vortex finder surface, foreign material deposits were found, as shown in Figure 2, along with observable changes to the surface condition. This phenomenon indicates that the actual operating conditions inside the cyclone may still exceed the thermomechanical resistance limits of the material. Factors such as non-uniform temperature distribution, solid-particle impingement velocity, operating-load fluctuations, and chemical interactions between flue gas and the metal surface are suspected to be the main causes of degradation.

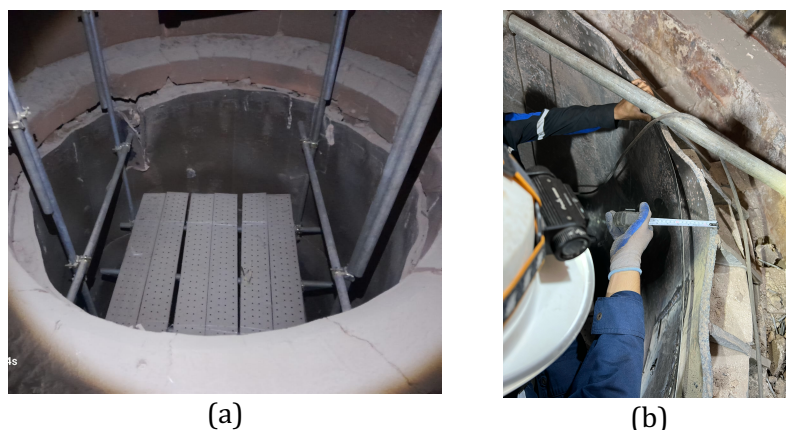


Figure 1. Vortex finder deformation during inspection: (a) vortex finder condition, (b) visual deformation check

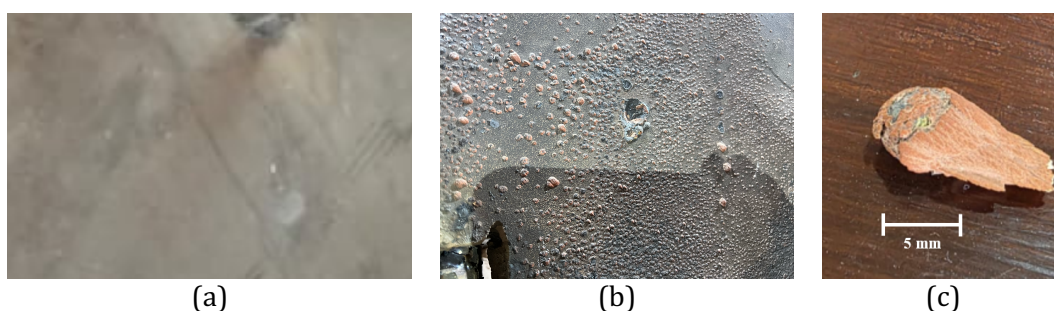


Figure 2. Comparison of (a) the vortex finder surface when first installed with (b) the surface after operation. (c) Foreign material found adhering to the vortex surface after operation

This study focuses on the failure analysis of a vortex finder component made of 253MA material in the CFB boiler of a 2 x 100 MW steam power plant at PLTU Sebalang, Lampung. Based on the boiler inspection on January 13, 2025, plastic deformation, material thinning, and foreign material deposits were found on the surface of the uppermost segment of the vortex finder after 6,548 hours of operation. The objectives of this study are to identify the failure characteristics, analyze the causes, explain the failure mechanism, and formulate technical recommendations to improve component reliability.

METHOD

The object of this study is the 253MA vortex finder cyclone component of Unit 2 at PLTU Sebalang, which had operated for 6,548 hours under material-layer temperatures of 850–930 °C and a main steam pressure of 9.8 ± 0.2 MPa. The research specimens were divided into four groups: installed vortex finder material (failed), remaining installed vortex finder material (new/reference), foreign material adhering to the vortex finder, and material adhering to the refractory wall. The testing was conducted comprehensively using Non-Destructive Testing (NDT) and Destructive Testing (DT) methods, including: (1) visual observation using a stereo microscope and DSLR camera to document surface conditions; (2) Positive Material Identification (PMI) using a PMI Master Smart Oxford instrument to verify chemical composition; (3) tensile testing using a Universal Testing Machine (UTM) with specimens of $L_0 = 50$ mm and $w_0 = 6$ mm; (4) Vickers microhardness testing with a 500 gf load at 10 measurement points; (5) microstructural observation using an optical metallurgical microscope at magnifications of 100×, 200×, and 500× after grinding, polishing, and etching preparation; (6) SEM-EDS analysis using a scanning electron microscope equipped with energy-dispersive spectroscopy to identify surface morphology and elemental composition; and (7) X-Ray Diffraction (XRD) analysis to identify mineral phases and crystalline compounds in the foreign material and refractory by matching them with the ICDD (International Centre for Diffraction Data) database. All tests were carried out at the LPPT UGM, ERIC UGM, and DTMI FT UGM laboratories in Yogyakarta.

Specimens were extracted from two locations: the deformed region at the lower end of the vortex finder (designated as “old material”) and a section of unused replacement material of identical specification (designated as “new material”). Tensile testing was performed in accordance with ASTM E8/E8M standards using two specimens per condition, oriented longitudinally relative to the component axis, at a crosshead speed of 2 mm/min. Microhardness testing followed ASTM E384 using a Vickers indenter with a 500-gf load and 15-second dwell time, with 10 measurement points per specimen to ensure representative averaging. Metallographic preparation involved sequential grinding with SiC papers (240–2000 grit), polishing with 1 μm diamond suspension, and electrolytic etching using a 10% oxalic acid solution at 6 V for 30 seconds to reveal the austenitic grain structure and carbide distribution. SEM-EDS analysis was conducted using a JEOL JSM-6510LA scanning electron microscope at an accelerating voltage of 20 kV with a working distance of 10 mm; EDS spectra were collected from three representative areas per specimen. XRD analysis was performed using a Rigaku MiniFlex 600 with Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$), a scanning range of $2\theta = 10^\circ\text{--}80^\circ$, a step size of 0.02° , and a scan speed of $2^\circ/\text{min}$.

RESULTS AND DISCUSSION

Visual Observation

Visual observation was conducted on the vortex finder component that had operated inside the circulating fluidized bed (CFB) boiler furnace at a working temperature range of approximately 850–950 °C. This examination aimed to identify early indications of material degradation before further testing was conducted. The observation focused on surface condition, dimensional changes, and any indications of crack initiation in the component.

Figure 3 shows the vortex finder component that failed due to deformation. From Figure 3, it can be observed that the component geometry changed from its initial relatively flat configuration to an uneven and distorted form. This condition indicates that the material experienced plastic deformation during service operation, likely driven by combined effects of high-temperature erosion and refractory deposit exposure within the CFB environment.



Figure 3. Deformation on the Vortex Finder Surface

The furnace operating environment, which contains solid particles such as bed material and fly ash, has the potential to induce abrasive wear mechanisms on the material surface. This condition allows gradual material erosion, which may result in localized thickness reduction in the component. This localized thinning may increase stress concentration in certain areas, thereby initiating crack formation.

Figure 4 shows foreign particles adhering to the vortex finder surface. These deposits exhibit shapes and colors similar to those adhering to the refractory wall. The particles have irregular morphologies, relatively small sizes, and are distributed across several surface areas. The markings in the figure indicate the observed particle locations on the component surface, and samples of vortex finder material exposed to the foreign deposits were collected for further analysis.

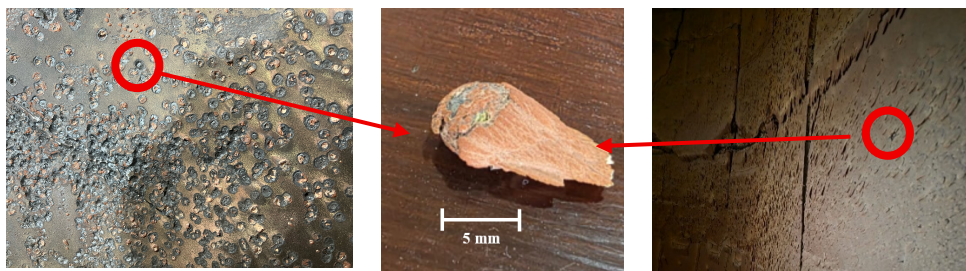


Figure 4. Foreign Material on the Vortex Finder

The foreign material found adhering to the vortex finder surface exhibits visual characteristics similar to the refractory material on the cyclone wall, indicating that the particles originated from the refractory layer that was eroded by bed material and fly ash impacts during operation. The detached refractory particles were carried by the high-velocity hot gas flow and possessed sufficient kinetic energy to strike and adhere to the vortex finder surface. The presence of these hard particles intensifies the abrasion mechanism on the metal surface and accelerates material degradation, indicating that the cyclone operating environment not only exposes the component to high temperatures but also simultaneously imposes mechanical loading in the form of solid-particle impacts. Further characterization of the foreign material was conducted using XRD.

Material Composition

The chemical composition of the vortex finder material was analyzed using a PMI Master Smart Oxford instrument (serial number 57T0028) with probe 66T0020. Figure 5 shows the vortex finder sample tested by PMI. Each sample was analyzed at least 3–4 times, as indicated by the white marks in Figure 5.

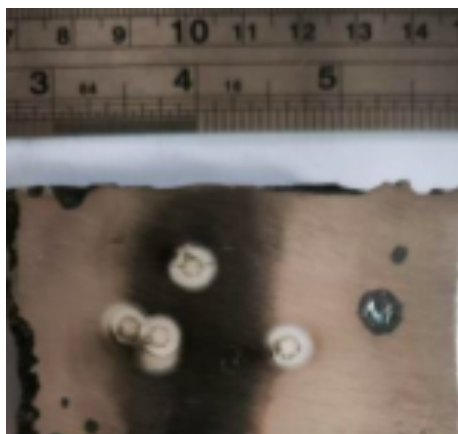


Figure 5. Material Sample After PMI Testing

The instrument was calibrated prior to the testing process using a calibration block. If the chemical composition results matched those of the calibration block, testing was then carried out on the test sample. If any mismatch appeared in the test results, the chemical composition value on the monitor would be marked with a red asterisk, indicating the discrepancy. In the vortex material test results, no indication of mismatch was found, meaning that all chemical composition measurements were valid. The chemical composition of the tested material is presented in Table 1.

Table 1. PMI Material Composition Test Results

Chemical Element (%)	253MA Test Result	253MA Standard	Description
Carbon (C)	0,0807	0,05 – 0,12	Within threshold value
Manganese (Mn)	0,615	≤ 1,00	Within threshold value
Silicon (Si)	1,75	1,40 – 2,50	Within threshold value
Phosphorus (P)	0,0373	≤ 0,045	Within threshold value
Sulfur (S)	0,0068	≤ 0,015	Within threshold value
Chromium (Cr)	19,8	20,0 – 22,0	Below standard
Nickel (Ni)	10	10,0 – 12,0	Within threshold value
Nitrogen (N)	0,293	0,12 – 0,20	Excessive
Cerium (Ce)	-	0,03 – 0,08	Not detected
Iron (Fe)	Balance	Balance	-

The analysis shows that the vortex finder material generally conforms to the characteristics of 253MA, with most elements falling within the standard specification range. Based on the test results, the Cr content was 19.8% and the Ni content was 10%; therefore, the material is categorized as an austenitic stainless steel with a typical chromium content of 16–26% and a nickel content of 10–22%.

The elements C, Mn, Si, P, and S are within the required limits. The Ni content still meets the specification, although it is at the lower limit. The Cr content is slightly below the standard, while the N content exceeds the specified limit. The Ce (cerium) element was not detected. Overall, the material is still classified as 253MA, with the main deviations being lower Cr, higher N, and the absence of Ce.

Tensile Testing

Tensile testing was conducted to determine the mechanical properties of the vortex finder material, particularly ultimate tensile strength, fracture elongation, and deformation behavior. The tests were performed on two types of specimens: samples taken from the installed vortex finder material exposed to operating conditions (aged material), and specimens from remaining installation material that had not been exposed to operating conditions (unexposed or new material). Figure 6 shows the vortex finder material samples after tensile strength testing.

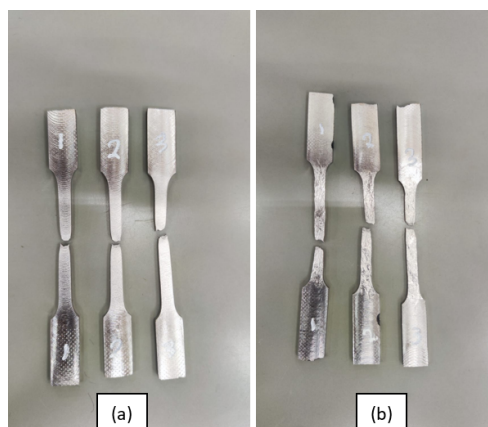
**Figure 6.** Tensile Test Specimens After Testing: (A) New Material And (B) Old Material

Figure 7 shows the tensile strength of the new and old materials. The new material had a tensile strength of 723.89 MPa, while the old material had a tensile strength of 677.84 MPa. The old material experienced a 6.36% decrease in tensile strength, attributed to thermal softening due to prolonged exposure to high operating temperatures. This softening is indicated by the enlargement of austenite grains, as discussed in the microstructural observation section. Softening due to temperature exposure is also confirmed by previous research ([Triasadian et al.](#),

2021; Widjanto et al., 2024).

Although the 6.36% decrease in tensile strength, the 8.62% decrease in elongation, and the 3.94% decrease in hardness are relatively modest in absolute terms, these changes are consistent with the expected mechanical property degradation patterns for austenitic stainless steels exposed to temperatures in the 850–950 °C range over extended periods. It should be noted that with only two specimens per condition, formal statistical significance testing is limited; however, the consistent directional trends across all three mechanical indicators (tensile strength, elongation, and hardness) provide converging evidence of genuine material degradation rather than random measurement variation.

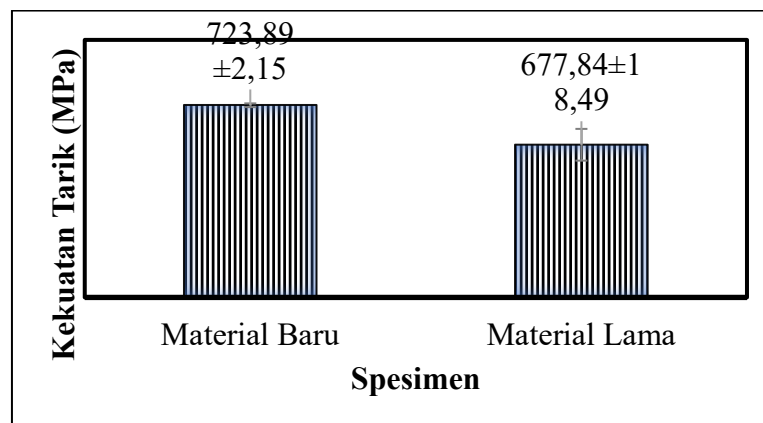


Figure 7. Tensile Strength of New and Old Materials

Figure 8 shows the fracture elongation values obtained from the test. The new material exhibits a relatively higher elongation at fracture compared to the old material. The old material experienced a 4.7% reduction in elongation. This indicates that the new material retains better plastic deformation capacity prior to fracture.

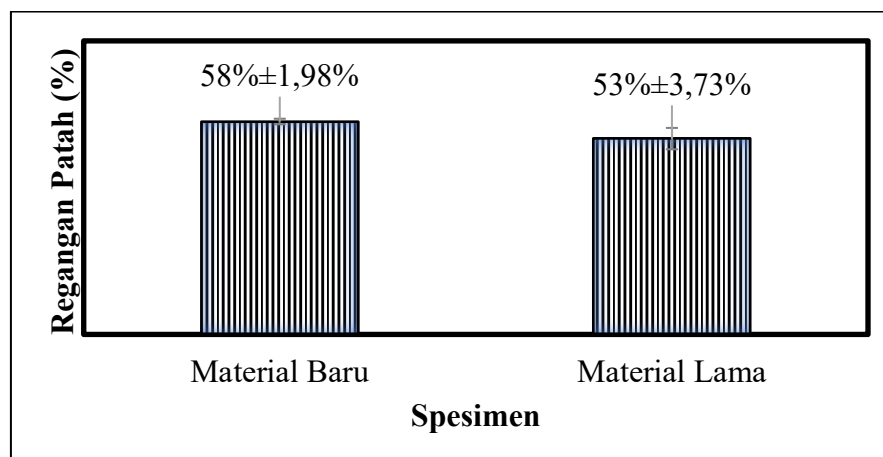


Figure 8. Fracture Elongation of New and Old Materials

High-temperature exposure can cause changes in the material's microstructure that reduce mechanical strength. Phenomena such as dislocation recovery, grain growth, and changes in precipitate distribution may decrease the material's ability to withstand mechanical loads. These conditions can accelerate deformation of the component during operation. The reduction in tensile strength and elongation values is confirmed through microstructural observation of the vortex finder material.

Microhardness

Figure 9 shows the sample used for hardness testing. Testing was conducted at 10 measurement points to obtain a representative average hardness value. Microhardness testing was performed using the Vickers method with a 300 g load. This test aimed to determine changes

in the material's mechanical properties at the microscale due to high-temperature exposure during operation.

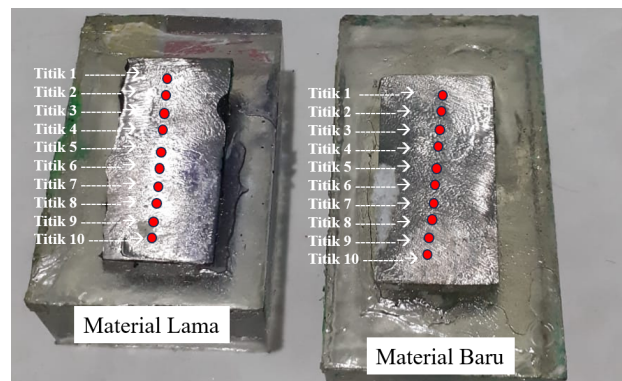


Figure 9. Microhardness Testing Sample.

Figure 10 shows the microhardness test results. The results indicate that the new material had an average hardness value of 218.84 HV, while the used (service-exposed) material showed an average hardness value of 210.21 HV. The service-exposed material exhibited a 3.94% decrease in hardness compared with the new material. This difference indicates a measurable reduction in material hardness after exposure to operating conditions in the CFB boiler environment.

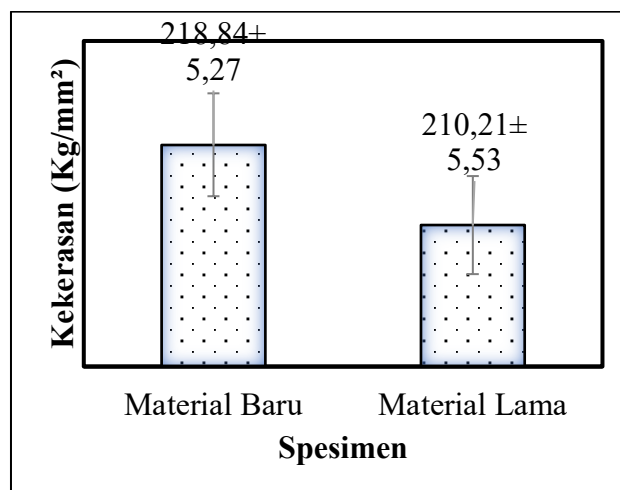


Figure 10. Hardness Test Results

The decrease in hardness indicates that the material underwent softening due to prolonged exposure to high temperatures. High operating temperatures can induce a recovery process in the crystal structure of the material, in which some dislocations are reduced or rearranged. This process can lower the hardness and strength of the material.

The distribution of hardness values at each measurement point also showed relatively small variations; thus, it can be concluded that the changes in mechanical properties occurred relatively uniformly across the tested area. This condition suggests that material degradation did not occur only locally but was influenced by high-temperature exposure experienced by the component during operation. This decrease in hardness is further confirmed through microstructural observation of the vortex finder material.

Microstructural Observation

Microstructural observation using an optical microscope at magnifications of 100×, 200×, and 500× was conducted after polishing and etching to compare the condition of the new and used materials. Figure 11 shows the observation results at 100× magnification, where the new material (Figures b and c) exhibits fine, uniform, and homogeneously distributed grains with thin, clearly

defined grain boundaries, without indications of plastic deformation or secondary recrystallization, reflecting an optimal microstructure with high strength and deformation resistance. Meanwhile, the used material (Figures e and f) shows grain coarsening with thickened and irregular grain boundaries, as well as indications of segregation along grain boundaries due to intensive atomic diffusion during long-term high-temperature exposure. These features indicate grain-boundary weakening and a potential reduction in mechanical properties.

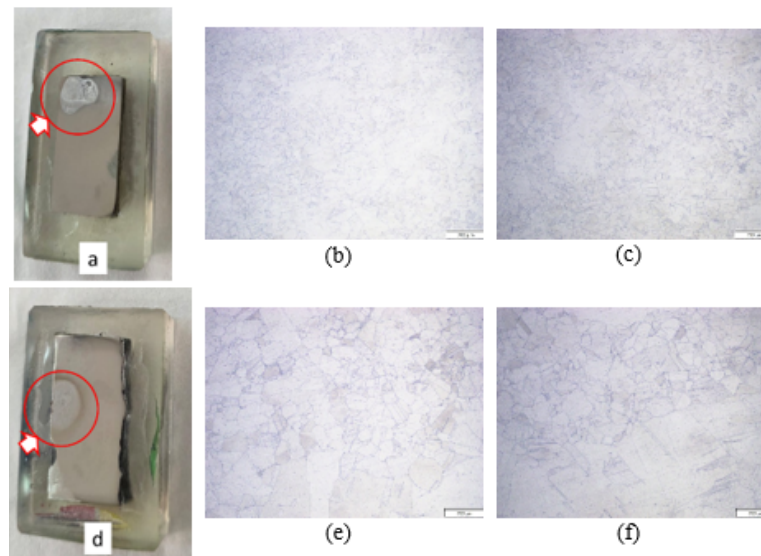


Figure 11. Microstructural Test Results at 100x Magnification for New and Old Materials

At 100× magnification, the new material showed a stable microstructure with fine, uniform grains and clear grain boundaries, without indications of deformation, while the old material exhibited grain coarsening, thickened and poorly defined grain boundaries, and grain distortion due to long-term high-temperature exposure, indicating a potential reduction in resistance to creep and cracking. Due to the limited resolution at 100× magnification, further observation was conducted at 200× magnification. Figure 12 shows the observation results at 200× magnification, where the new material (Figures a–c) exhibited fine and uniform grains with firm and clearly defined grain boundaries, indicating a low level of plastic deformation and the material's ability to maintain its initial strength in accordance with the Hall–Petch relationship. Meanwhile, the old material (Figures d–f) showed larger and irregular grains with widened and less well-defined grain boundaries, accompanied by indications of slip lines due to repeated mechanical stress. This condition reduces the number of effective grain boundaries, causing hardness and strength to decrease, although ductility tends to increase.

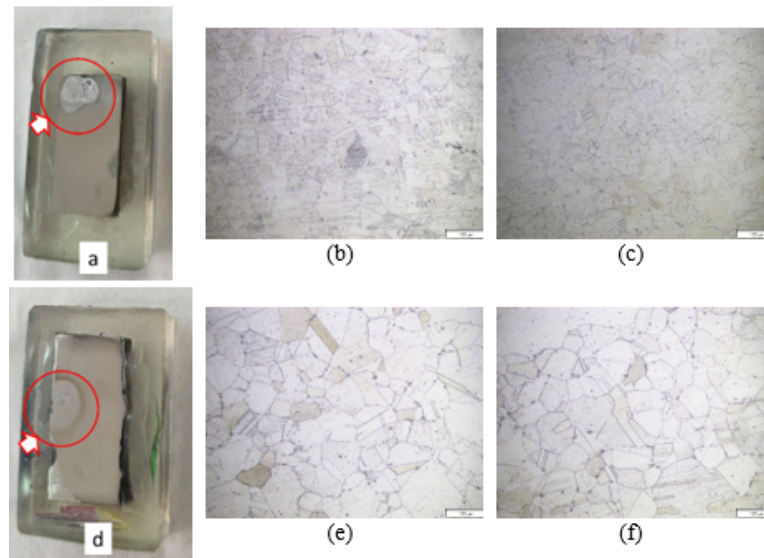


Figure 12. Microstructural Test Results At 200x Magnification for New and Old Materials

Comparison of the two conditions shows that the new material has finer grains with sharp grain boundaries, which correlate with higher mechanical strength, while the old material experienced microstructural degradation due to heating and service exposure. To strengthen the analysis, further observations were conducted at 500× magnification. Figure 13 shows the results at 500× magnification, where the new material (Figures b and c) exhibited fine, uniform, and equiaxed grains with thin, well-defined grain boundaries and minimal microdefects, indicating good structural integrity and high resistance to crack initiation. Meanwhile, the old material (Figures e and f) showed grain growth with larger, irregular, and elongated grains, accompanied by thickened grain boundaries, accumulation of secondary phases, and an increased number of microdefects in the form of voids and indications of microcracks along grain boundaries. This condition indicates that grain boundaries have become weakened regions due to stress concentration, reducing the material's ability to resist deformation and significantly increasing the potential for intergranular crack propagation.

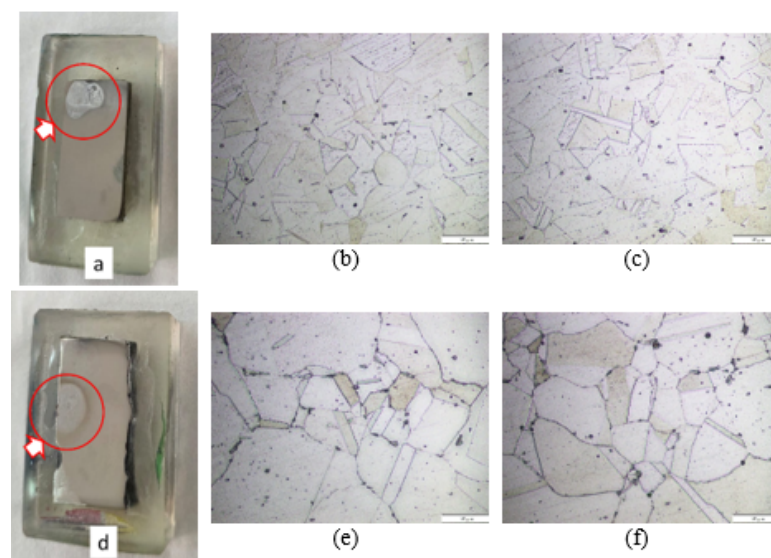


Figure 13. Microstructural Test Results At 500x Magnification for New and Old Materials

Grain diameter enlargement occurs because, at elevated temperatures, atoms have sufficient energy to diffuse through the crystal lattice. This diffusion allows smaller grains to merge into larger grains, thereby reducing the system's total energy. The relationship between grain size and the mechanical properties of the material can be explained using the Hall-Petch relationship, as expressed in Equation (5.1).

$$\sigma_y = \sigma_0 + k \cdot d^{-1/2} \quad (5.1)$$

where:

σ_y = yield strength

d = grain diameter

k = material constant

According to the Hall–Petch relationship, a new material with a smaller grain size contains more grain boundaries that act as barriers to dislocation movement, resulting in higher strength and hardness than the old material, as confirmed by tensile and microhardness test results. In the old material, grain coarsening due to high-temperature exposure reduces the number of effective grain boundaries, allowing dislocations to move more freely and making the material softer and more susceptible to plastic deformation. This reduction in mechanical properties is further aggravated by dislocation recovery, which decreases dislocation density, and precipitate coarsening at grain boundaries, which weakens the precipitation-strengthening mechanism. Overall, these processes produce a softer material that is more prone to plastic deformation under high-temperature operating conditions (Alviana et al., 2023).

SEM + EDS/EDX

Scanning Electron Microscopy (SEM) combined with Energy Dispersive Spectroscopy (EDS) was performed to identify the elemental composition of the vortex finder material and evaluate chemical changes after exposure to high-temperature conditions and the boiler operating environment. The analysis was conducted on two samples: the remaining installed vortex finder material (new material) and the in-service vortex finder material (old material). Figure 14 shows the area selected for SEM-EDS testing. The old material sample was taken from a region containing foreign deposits adhering to the vortex wall. The samples were tested under dry conditions, with maximum dimensions of 10 mm (diameter, length, width, and height).



Figure 14. SEM-EDX Test Sample

Figure 15 shows the Scanning Electron Microscopy (SEM) observation results for the new material. The surface morphology of the new material in Figure 5.13 is dominated by relatively uniform, elongated, and parallel lines, indicating manufacturing traces such as machining or finishing processes. These grooves have relatively shallow depth and a homogeneous distribution and do not show significant plastic deformation. Some small particles scattered across the surface are likely residual process debris or light surface contamination, but they do not form large agglomerations. In addition, no significant indications of microcracks or delamination are observed. This indicates that the material remains in a structurally stable condition, with a relatively intact surface and no degradation due to thermomechanical loading.

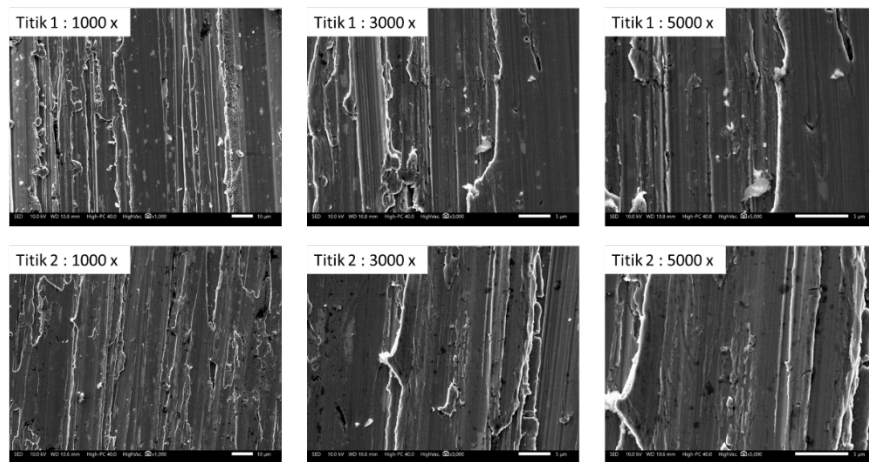


Figure 15. SEM Results of New Material

Figure 16 shows the Scanning Electron Microscopy (SEM) observation results for the old material. The surface morphology of the old material in Figure 5.14, which had been exposed to service conditions, showed a higher level of damage. Parallel-line patterns were still visible; however, they had become distorted, widened, and irregular, indicating plastic deformation due to frictional loading and operational pressure during service. Surface delamination, material build-up, and the formation of coarse particles adhering to and spreading unevenly were also observed. This phenomenon indicates the dominance of wear mechanisms such as adhesive wear and abrasive wear.

In addition, several areas showed early indications of microcracks and pits (small depressions), which could develop into crack initiation sites. The rougher and more heterogeneous surface indicates that the material experienced accumulated plastic deformation and possible long-term high-temperature exposure, which accelerated the degradation process.

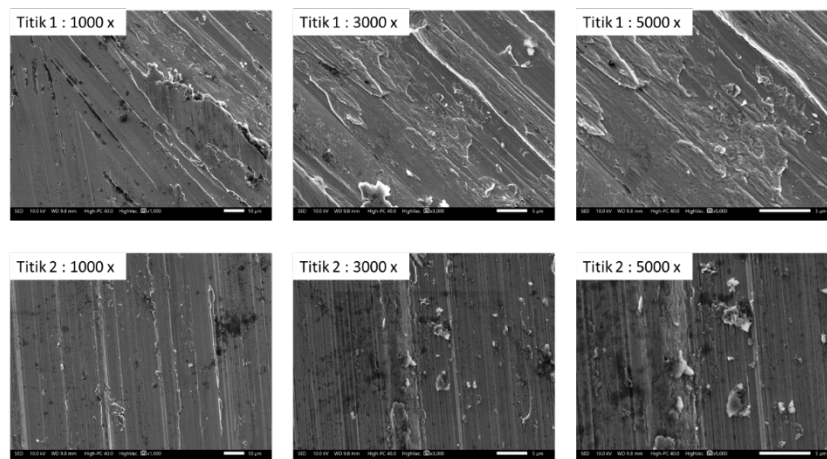


Figure 16. SEM Results of Old Material

The SEM results show that the new 253MA material had a relatively smooth, homogeneous surface and was free from indications of severe deformation, while the old material underwent significant morphological changes, including increased roughness, plastic deformation, wear, oxidation, and the appearance of micro-defects, which increase the potential for crack initiation and propagation. Figure 5.15 presents the Energy-Dispersive X-ray Spectroscopy (EDS) analysis results for the new material, where the main detected compositions were Fe (63.03%), Cr (21.16%), and Ni (9.30%), which conform to the standard specification of 253MA material (Cr content of 20–22% and Ni content of 10–12%), confirming that the new material had not undergone chemical composition changes due to the operating environment.

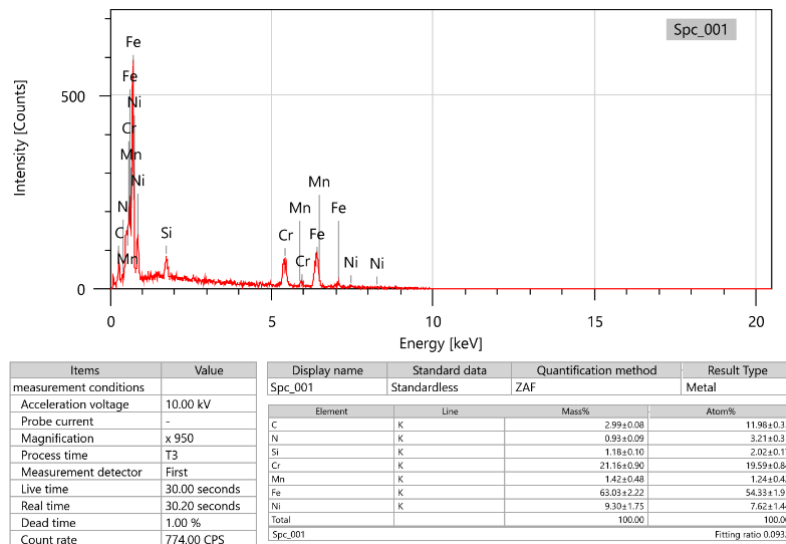


Figure 17. SEM-EDS Test Results of New Material

The elemental composition obtained from the EDS testing shows that the new vortex finder material has chemical composition characteristics that generally remain close to the manufacturer's 253MA material specification. This condition indicates that the new material has not experienced compositional changes due to operating conditions.

Figure 18 shows the EDS analysis results for the old material sample. The results indicate that the main elements composing the material were Fe, Cr, and Ni, with approximate contents of 64.59%, 19.48%, and 7.60%, respectively. These values indicate a slight decrease in Cr and Ni contents compared with those of the new material.

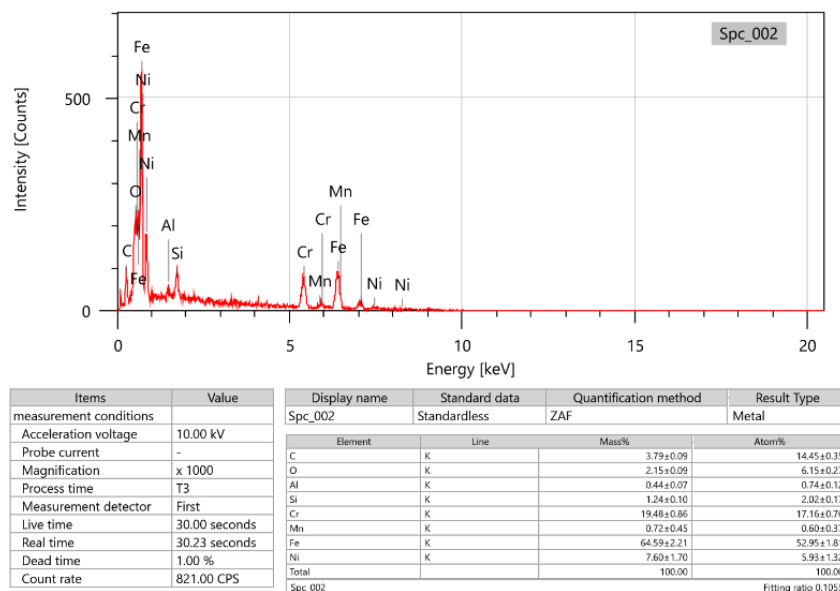


Figure 18. SEM-EDS Test Results of Old Material

EDS analysis of the old material showed a relative decrease in Cr and Ni content compared with the new material, indicating high-temperature oxidation effects, in which Cr reacts with oxygen to form a protective Cr_2O_3 oxide layer, thereby reducing its measurable surface content. In addition, significant increases in Si (1.24%), Al (0.44%), and O (2.15%) were detected in the old material, indicating surface contamination due to interaction with Al_2O_3 - and SiO_2 -based refractory particles from the furnace operating environment, while also confirming ongoing high-temperature oxidation on the material surface. The presence of Si, Al, and O will subsequently be confirmed through XRD analysis.

XRD Analysis of Foreign Material

The figure shows the sample subjected to X-ray diffraction (XRD) testing. XRD analysis was conducted on foreign material adhering to the vortex finder and on material attached to the refractory wall to identify the crystalline phases present and evaluate conformity with the refractory specifications used in the vortex finder component.



Figure 19. XRD Test Sample

Figure 20 presents the standard International Centre for Diffraction Data (ICDD) Powder Diffraction File (PDF) database references. The analysis was conducted by matching the diffraction patterns obtained from testing with the standard International Centre for Diffraction Data (ICDD) Powder Diffraction File (PDF) database, so that each diffraction peak could be identified as a representation of a specific crystal structure.

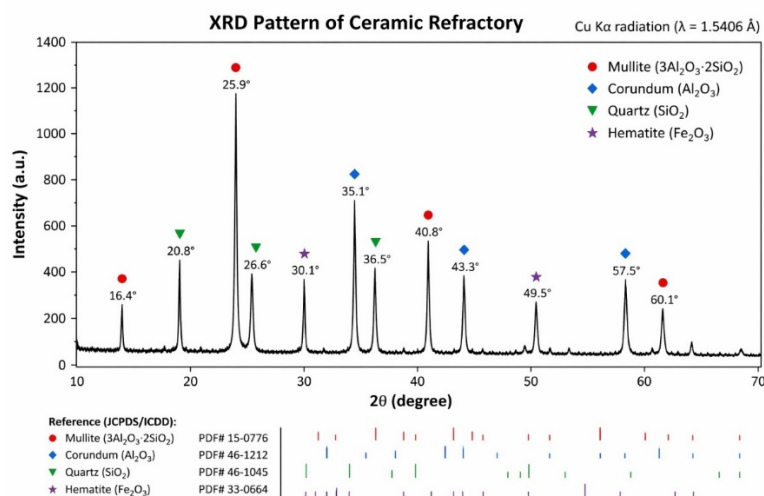


Figure 20. Standard International Centre for Diffraction Data (ICDD) Database

Figure 21 shows the XRD results for the foreign material adhering to the vortex finder and the refractory material. Qualitatively, the diffraction patterns in both graphs are almost identical. The obtained diffraction patterns show sharp peaks in the 2θ angle range from 10° to 70° , indicating that the material is dominated by crystalline phases. Based on matching with ICDD PDF database data, the dominant phase identified is mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), indicated by characteristic peaks at approximately 16.4° , 25.9° , 40.8° , and 60.1° . In addition, a corundum (Al_2O_3) phase was also detected at approximately 35.1° , 43.3° , and 57.5° . The dominance of mullite and corundum is highly consistent with the chemical composition of the refractory material used, namely approximately 73% Al_2O_3 and 23% SiO_2 , where the combination of these two oxides thermodynamically forms mullite as a stable phase at high temperatures. Therefore, these XRD results confirm that the tested material is an alumina-silica-based refractory (high-alumina refractory) that conforms to the design specification (Hadining & Basuki, 2023).

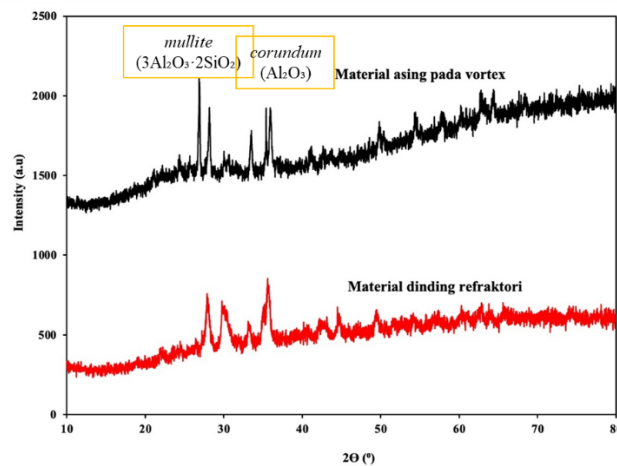


Figure 21. XRD Results of Foreign Material and Refractory

The XRD results not only confirm that the foreign material adhering to the vortex finder is an alumina–silica-based refractory that meets the specification, but also indicate the influence of the operating environment on changes in the material structure. The combination of foreign material, amorphous phase formation, and localized hotspot conditions is a major factor contributing to microstructural changes in the vortex finder, which in the long term may develop into a material failure mechanism.

Material Failure Mechanism

(Ismail et al., 2026; NUGROHO, 2019) Based on the multi-method approach, the failure mechanism of the vortex finder occurred gradually and synergistically. High-velocity solid-particle erosion caused material thinning and increased surface roughness, which then facilitated the accumulation of refractory-based foreign material deposits (containing Si, Al, and Ca). These deposits acted as thermal insulators that triggered localized hotspot formation, thereby accelerating microstructural degradation in the form of grain coarsening, carbide precipitation at grain boundaries, and creep mechanisms, as reflected in the decrease in tensile strength and hardness. Extreme thermal conditions also accelerated oxidation and corrosion, particularly due to interactions between alkali metals and chlorine species with the protective Cr_2O_3 oxide layer. As the material strength decreased, the combination of thermal and mechanical stresses triggered microcrack initiation in both intergranular and transgranular modes, which then developed into macrocracks and ultimately led to structural failure. All of these mechanisms mutually reinforce one another, forming a damage-acceleration loop that significantly shortens the component service life.

It is important to distinguish between failure mechanisms that are directly demonstrated by the test data and those that remain interpretive. Directly demonstrated findings include: (1) plastic deformation and material thinning confirmed by visual observation; (2) mechanical property degradation confirmed by tensile, elongation, and hardness tests; (3) grain coarsening confirmed by optical microscopy; (4) surface roughening and microcrack initiation confirmed by SEM; and (5) refractory deposit adherence confirmed by XRD phase matching. In contrast, the following mechanisms are proposed as contributing factors based on indicative evidence rather than direct measurement: (a) localized hotspot formation, which is inferred from the pattern of refractory accumulation and deformation geometry but has not been validated by in-situ temperature monitoring; (b) creep deformation, which is suggested by the plastic deformation morphology and operating temperature range but has not been confirmed by dedicated creep testing or specialized fractography; and (c) chlorine/alkali-induced corrosion, which is suggested by minor elemental traces in EDS but not conclusively established from the XRD data presented.

CONCLUSION

This study presents a comprehensive failure analysis of a 253MA vortex finder in a CFB boiler after 6,548 operating hours at 850–950°C. The principal findings are: (1) failure manifested as plastic deformation and material thinning caused by high-velocity solid-particle erosion; (2) mechanical properties degraded measurably, with tensile strength decreasing by 6.36%, elongation by 8.62%, and hardness by 3.94%; (3) microstructural degradation in the form of grain coarsening and carbide precipitation was confirmed by optical microscopy; (4) SEM-EDS revealed surface roughening, early microcrack formation, and compositional changes; and (5) XRD confirmed that the adhering foreign material originated from alumina–silica refractory material. While localized hot-spot formation and creep deformation are proposed as contributing mechanisms based on indicative evidence, these require further validation through in situ temperature monitoring and dedicated creep testing. Recommendations include implementing erosion-resistant coatings or higher-grade alloys in critical zones, conducting periodic refractory integrity assessments, and adopting condition-based inspection protocols with defined interval thresholds based on operating hours and temperature exposure.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to Universitas Gadjah Mada and the supporting laboratories, including LPPT UGM, ERIC UGM, and DTMI FT UGM, for facilitating the material testing and analysis required in this study. Appreciation is also extended to PLTU Sebalang for providing access to the 253MA vortex finder component and operational data, as well as to all technical staff and related parties who supported the visual inspection, PMI, tensile testing, microhardness testing, optical microscopy, SEM-EDS, and XRD analysis conducted in this research.

AUTHOR CONTRIBUTION STATEMENT

Martua Haposan Echo Sihite conceptualized the study, collected field data, prepared test specimens, conducted failure analysis, interpreted the mechanical and microstructural findings, and drafted the manuscript. Kusmono contributed to the research design, supervised the testing methodology, validated the material analysis, reviewed the failure mechanism interpretation, and critically revised the manuscript. Both authors reviewed and approved the final version of the manuscript for publication.

REFERENCES

- Alviana, R. M., Anwar, M. S., & Siradj, E. S. (2023). Evaluation Of Microstructure High Chrome Austenitic Stainless-Steel Grade 253ma After Creep Test At Temperature Of 700 C. *Jurnal Pendidikan Teknologi Kejuruan*, 6(1), 41–47.
- Arjunwadkar, A., Basu, P., & Acharya, B. (2016). A Review Of Some Operation And Maintenance Issues Of Cfb Boilers. *Applied Thermal Engineering*, 102, 672–694.
- Baskoro, Y., & Wardhana, M. (2026). Peningkatan Proses Pemeliharaan Pada Pembangkit Listrik Pltu Jeranjang Ntb Dengan Memadukan Proses Outage Management Framework Dan Design Thinking. *Jurnal Locus Penelitian Dan Pengabdian*, 5(3), 1599–1617.
- Basu, P. (2006). *Circulating Fluidized Bed Boiler Bt - Combustion And Gasification In Fluidized Beds*. CRC Press.
- Dagdag, O., Haldhar, R., Thakur, A., Daoudi, W., Berisha, A., Berdimurodov, E., & Kim, H. (2025). Corrosion In The Power Plant Industry. *Industrial Corrosion: Fundamentals, Failure, Analysis And Prevention*, 105–130.
- Darmawan, S., & Wibowo, P. (2024). Analisis Perbandingan Kinerja Pembangkit Listrik Tenaga Surya Dan Pembangkit Listrik Tenaga Uap Pada Lingkungan PT. RAPP. *Jurnal Engine: Energi, Manufaktur, Dan Material*, 8(2), 161–174.
- Facheruddin, M. (2023). *Analisa Kegagalan Material Pipa Superheater Pada Boiler Type CFB (Circulating Fluidized Bed)*.
- Hadining, W. N., & Basuki, E. A. (2023). Pengaruh Pelapisan Aluminida Paduan Ti-47al-2nb-2cr-0.5zr-0.5y Terhadap Oksidasi Siklik Pada Temperatur 900, 1000, Dan 1100 C. *Journal Of Metallurgical Engineering And Processing Technology*, 146–158.

- Hagman, H., Bostrom, D., Lundberg, M., & Backman, R. (2019). Alloy Degradation In A Co-Firing Biomass CFB Vortex Finder Application At 880 C. *Corrosion Science*, 150, 136–150.
- Ismail, I., Saiful, M. S., Aprilia, S., & Mulana, I. F. (2026). *Material Komposit*. USK Press.
- Jamilatun, S., Rhomadoni, F. R., Astuti, E., Wardhana, B. S., Idris, M., & Auliasari, P. A. (2025). Peran Manajemen Energi Terhadap Efisiensi Konsumsi Listrik Rumah Tangga Di Indonesia. *Prosiding Semnastek*.
- Kementerian ESDM. (2022). *Content Handbook Of Energy And Economic Statistics Of Indonesia 2022*.
- Konist, A. (2023). Investigation Of Fouling And Corrosion Of Low-Temperature Reheater In A CFBC Boiler. *Fuel*, 338, 127373.
- Malik, E. (2024). *Pengaruh Lapisan Erosion Shield Terhadap Efektivitas Perpindahan Panas Pada Primary Superheater Boiler Unit 7 Di PT. PLN Indonesia Power UBP Suralaya*.
- Maulana, N. U. R. R. (2026). Analisis Implementasi Preventive Maintenance Pada Boiler Unit 3 Di PT CCEPC. *Prosiding Seminar Nasional Energi, Telekomunikasi Dan Otomasi (SNETO)*, 121–128.
- Mawuntu, D. J., Makasarat, O., Koraag, R. A., Poli, A. E., & Najooan, H. K. (2024). Analisa Daya Mampu Pasokan Listrik Di Pulau Marampit Kabupaten Kepulauan Talaud. *Riggs: Journal Of Artificial Intelligence And Digital Business*, 3(2), 1–5.
- Negara, P. L. (2024). *Annual Report PLN 2024*.
- Nugroho, R. F. D. W. I. (2019). *Hak Kreditor Separatis Menurut Pasal 55 Ayat (1) Juncto Pasal 56 Ayat (1) Dan Pasal 59 Uu No 37 Tahun 2004 Tentang Kepailitan Dalam Eksekusi Barang Jaminan Milik Debitor*.
- Pamungkas, I., Irawan, H. T., & Pandria, T. M. A. (2021). Implementasi Preventive Maintenance Untuk Meningkatkan Keandalan Pada Komponen Kritis Boiler Di Pembangkit Listrik Tenaga Uap. *Vocatech: Vocational Education And Technology Journal*, 2(2), 73–79.
- Triasdian, Y., Busairi, N. A., Parningotan Ts, H., & Muflikhun, M. A. (2021). Failure Analysis Of Water Wall Tube In Circulating Fluidized Bed Boiler. *Aip Conference Proceedings*, 2403(1), 30001.
- Widjajanto, T., Darmadi, D. B., Irawan, Y. S., & Gapsari, F. (2024). Failures Analysis Of Tube Coating In Circulating Fluidized Bed (CFB) Boiler. *Heliyon*, 10(4).
- Yohana, E., Tauviqirrahman, M., Prakoso, B. K., Choi, K. H., & Charles, H. (2023). Karakteristik Dan Performa Cyclone Separator Dengan Penambahan Vortex Finder (Tappered Out-Cylinder In) Dan Variasi Pendinginan Pada Cone Cyclone Dengan Menggunakan Simulasi Numerik. *Jurnal Teknik Mesin*, 11(2), 191–204.