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FAILURE CASE STUDY SERIES PART TWO: FAILURE ANALYSIS OF ROLLER GUIDES IN A WIRE ROD ROLLING MILL

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ABSTRACT

The paper aims to present the root cause of failure of roller guides from the wire rod and coil rolling mill during normal operation. A comprehensive failure investigation was conducted following standard metallurgical procedures, including visual inspection, hardness testing, chemical analysis, optical microscopy, stereomicroscopy, scanning electron microscopy (SEM–EDS) characterization, and inclusion rating according to ASTM E45. The investigation concludes that the primary root cause of failure was the use of D3 tool steel, which is unsuitable for components subjected to severe thermal cycling, resulting in progressive thermal fatigue damage and eventual catastrophic fracture. Moreover, the election of D2 or other Mo-V alloyed hot-work tool steels, combined with appropriate surface hardening, is recommended to enhance service life under rolling mill operating conditions.

KEYWORDS: failure analysis, thermal fatigue, roller guides, OM, SEM, EDS

1. Introduction

Roller guides in high-speed wire rod mills are subjected to extreme thermomechanical loading, given that billet temperatures routinely exceed 1000 °C while guide roll rotational velocities surpass 80–85 m/s. Moreover, these aggressive operating conditions amplify thermal gradients, surface oxidation, and vibrational stresses, all of which accelerate component degradation. Aside from the aforementioned effects, recent industrial analyses identify cooling water pressure instability, vapor film shielding, oil contamination within the cooling water, misalignment, and inadequate material selection as the most critical contributors to premature roller guide failure [1, 2, 14]. Above all, when cooling pressure drops below the ~0.5 MPa threshold or when water jets impinge at sub-optimal angles, persistent steam film layers develop, drastically diminishing heat extraction and fostering thermal fatigue fire cracking [1, 2].

Furthermore, complementary investigations across wire rod finishing units demonstrate that cobble events, gearbox bearing failures, overheating transients, and rapid load fluctuations intensify crack initiation by superimposing irregular stress cycles on already overheated surfaces [3, 15]. Correspondingly, studies addressing tungsten carbide and cast roll failures similarly correlate fire crack networks with repeated thermal cycling, showing that even modest increases in surface temperature accelerate crack propagation in line with classical thermal fatigue mechanisms [4, 5, 16]. Beyond that, both field observations and modeling research indicate that roll cooling configuration, oxide scale behavior, and surface residual stresses exert dominant control over crack advance rates in hot rolling environments [5, 16].

The material system used for roller guides likewise exerts a profound influence on service life. Cold-work tool steels standardized under ASTM A681 are commonly employed, with D2 and D3 frequently encountered in industrial guide roll fabrication [6, 7, 17]. Apart from compositional distinctions, these steels exhibit notable performance differences. D2, alloyed with molybdenum and vanadium, forms fine secondary carbides and demonstrates superior thermal fatigue resistance at elevated temperatures [7, 8, 18]. In contrast, D3 lacks Mo and V, relying instead on elevated carbon and chromium levels that promote coarse Cr-rich carbides. This microstructure yields high wear

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resistance at room temperature but results in low fracture toughness and poor high-temperature fatigue resistance [7, 8]. Moreover, recent studies show that D3's carbide dissolution behavior differs significantly from that of D2. Although multi-cycle austenitizing can improve hardness uniformity, it does not mitigate D3's intrinsic vulnerability to brittle thermal shock cracking [9, 10].

Furthermore, thermal spray and surface engineering approaches—including molybdenum-based coatings—have shown promising improvements in surface hardness and wear resistance for D-series substrates, offering potential as auxiliary life-extension strategies when base material limitations cannot be entirely eliminated [11, 19]. Correspondingly, modern fracture mechanics literature highlights that short-crack behavior, mixed-mode loading, and microstructure-sensitive crack growth models play central roles in predicting crack evolution in hot cyclic environments [12, 13, 20]. These insights align closely with SEM analyses of failed roller guides, which commonly exhibit beach marks, intergranular facets, micro-oxidized fire crack ligaments, and secondary branching—features characteristic of thermally driven fatigue.

Taken together, contemporary evidence demonstrates that improving roller guide reliability necessitates an integrated materials engineering and process control framework: (1) selecting Mo–V-bearing tool steels (e.g., D2) or alternative hot-work grades; (2) optimizing cooling jet pressure, geometry, and water cleanliness; and (3) applying surface hardening or thermal spray treatments to suppress crack nucleation under high-temperature cyclic contact conditions. Above all, this comprehensive methodology directly addresses the key root causes of premature failures in RM wire rod guide systems.

2. Experimental procedure

The chemical composition was determined with the optical emission spectrometer ARL 3460, driven by the new OXSAS analytical software. The equipment is designed to meet the specific needs of users in the metals industry, with OXSAS providing simple one-click routine analysis launch and full traceability. The test method (ASTM E415-21) facilitates the simultaneous determination of 21 alloying and residual elements in carbon and low-alloy steels. This method is suitable for routine control analysis in iron and steelmaking operations and can be applied to processed materials such as chill-cast, rolled, and forged specimens. The hardness test was performed with Universal Hardness Testing Machine KB150 R - Digital Rockwell. Stereo microscopy, optical microscopy, scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) facilities were extensively presented in our previous work [21].

The material AISI D2 Tool Steel is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium as per ASTM A 681 standard. It is the most widely used steel among the group D steels. It has high abrasive wear resistance, high compressive strength, good through-hardening properties, high stability during hardening, and good resistance to tempering-back. AISI D2 is often supplied in the annealed conditions.

3. Results and discussion

The analysis followed seven basic steps:

- Visual Inspection: The components were first examined for visible indicators such as fracture surface morphology, crack propagation patterns, discoloration, unusual wear, corrosion, bending, misalignment, or scoring marks that could suggest mechanical or environmental influence.
- Specimen Selection and Preservation: Critical areas of interest were carefully identified, marked, and preserved to ensure their integrity for detailed analysis.
- High-Stress Area Identification: Regions with potential high-stress concentration were assessed as likely crack initiation sites, providing key insight into the failure mechanism.
- Chemical Analysis and Standard Comparison: The chemical composition of the material was analyzed and compared against applicable standards to check for deviations or non-conformities.
- Hardness Testing: Hardness measurements were conducted and evaluated against standard requirements to detect abnormal hardness zones that may indicate improper processing.
- Optical Microscopy: Metallographic examination was performed to assess the steel's microstructure, inclusion content, and any signs of improper heat treatment, abnormal grain structure, or internal cleanliness issues.
- Scanning Electron Microscopy (SEM) and EDS Analysis: SEM analysis, coupled with Energy Dispersive Spectroscopy (EDS), was used to study the fracture surface at high magnification, identifying crack initiation points, fracture modes (e.g., brittle or ductile), and any compositional anomalies at the crack origin.

3.1. Visual inspection

The guides failed during normal operation without any blockages in the rolling process (Figure 1). Visual inspection revealed prominent fire cracks on the rolling face of the component. These thermally

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induced surface cracks are typically caused by rapid and repeated heating and cooling cycles during rolling operations, leading to localized thermal fatigue (Figure 2).

Such fire cracks serve as stress concentrators and can significantly reduce the fatigue resistance of the material. Under cyclic loading, they provide favourable conditions for fatigue crack initiation and propagation, which can ultimately result in premature fatigue failure of the component.

Fig. 1. *Broken guide at site*

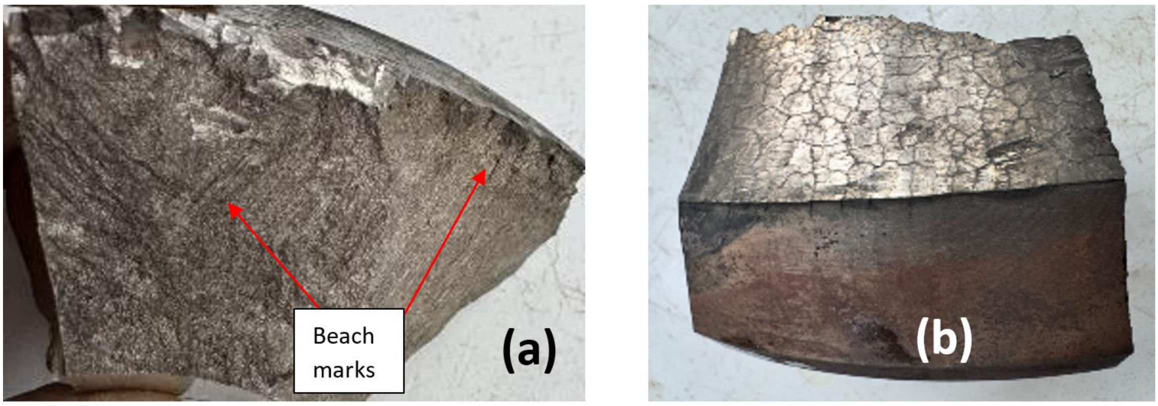

Fig. 2. *Failure surface: beach marks (a), fire cracks (b)*

Visual inspection revealed prominent fire cracks on the rolling face of the component. These thermally induced surface cracks are typically caused by rapid and repeated heating and cooling cycles during rolling operations, leading to localized thermal fatigue.

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3.2. Chemical analysis

A Thermo Scientific ARL 3460 Advantage optical emission spectrometer was employed to quantify the elemental composition, using the ASTM E415-21 standard procedure for spark atomic emission analysis of carbon and low-alloy steels [21].

According to chemical composition determined in Spectral test machine the Steel Grade used for Roller guide is specific steel grade D2 - ASTM-A681-08-Standard-Specification-For-Alloy-Tool-Steel-Cold-work-Hot-Work-Plastic (Table 1).

Impact of Molybdenum in Tool Steel for High-Temperature Applications: Molybdenum (Mo) plays a critical role in enhancing the high-temperature performance of tool steels, especially those used in hot working applications such as rolling mill rolls, forging dies, and extrusion tools. Its addition brings several metallurgical benefits that directly improve resistance to thermal fatigue, a common failure mechanism in these environments.

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Metallurgical Contributions of Molybdenum are the following: Improved High-Temperature Strength and Creep Resistance; Forms stable carbides (e.g. Mo_2C) that maintain hardness and strength at elevated temperatures; Reduces softening during cyclic heating, preserving the tool's structural integrity. Thermal Fatigue Resistance: Molybdenum increases the hot hardness and improves resistance to thermal cycling, which is essential for preventing surface crack initiation (fire cracks); It delays crack propagation by enhancing the steel's toughness and resistance to microstructural degradation under thermal stress. Reduced Thermal Expansion Mismatch: Molybdenum contributes to a more stable microstructure during heating and cooling cycles, minimizing thermal strain and associated fatigue cracking. Carbide Stability and Secondary Hardening: Molybdenum supports the formation of finely dispersed carbides, improving wear resistance without excessive brittleness. Promotes secondary hardening during tempering, further enhancing thermal resistance. Resistance to Tempering Embrittlement: Mo helps prevent temper embrittlement and intergranular cracking under prolonged service at high temperatures.

Table 1. *Roller guide chemical composition*

Element	Composition Range (wt.%)	D2 - ASTM-A681-08	D3 -ASTM-A681-08
Carbon (C)	2.125	1.4-1.6	2.0-2.35
Manganese (Mn)	0.303	0.1-0.6	0.10-0.60
Phosphorus (P)	0.04	Max 0.030	Max 0.030
Sulfur (S)	0.028	Max 0.030	Max 0.030
Silicon (Si)	0.655	0.10-0.60	0.10-0.60
Chromium (Cr)	12.213	11.0-13.00	11.0-13.00
Nickel (Ni)	0.135	Ni + Cu max 0.75%	Ni + Cu max 0.75%
Aluminum (Al)	0.0041	-	
Nitrogen (N)	0.0120	-	
Molybdenum (Mo)	0.0261	0.7-1.20	Max 1.0
Vanadium (V)	0.024	0.50-1.0	Max 1.0
Titanium (Ti)	0.0132		
Copper (Cu)	0.070	Ni + Cu max 0.75%	Ni + Cu max 0.75%
Cev	4.64	-----	-----

Overall, molybdenum is a key alloying element in tool steels used for high-temperature applications due to its ability to increase thermal fatigue resistance, maintain hardness under heat, and improve structural stability. Its inclusion is essential in environments where tools are exposed to cyclic thermal loading, helping prevent fire cracks and fatigue failures, and thus extending the tool's service life.

3.3. Hardness Test

Hardness testing was performed on the roller surface [rolling face] region as well as the core region to evaluate potential hardness variations. However, no significant difference could be observed between the two regions. Both areas revealed very high hardness, on the order of approximately 60 HRC (Figure 3).

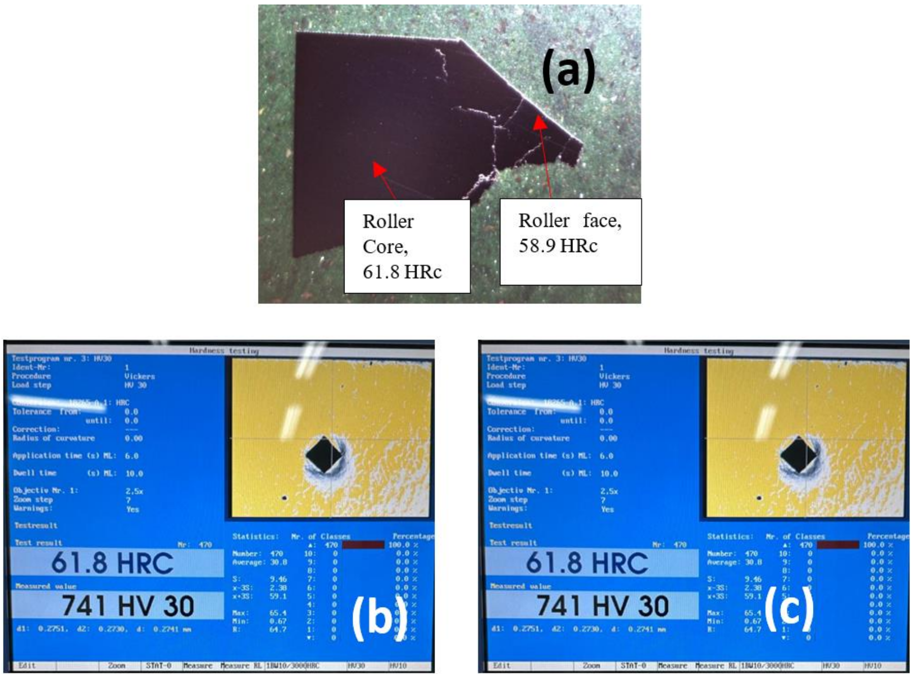

Fig. 3. *Vickers and Rockwell hardness (a) roller core, (b) roller side*

3.4. Stereomicroscopy

Stereomicroscopy plays an important role in failure analysis, quality control, and industrial applications (Figure 4). With its high depth perception, large working distance, and ease of use, it remains an essential instrument across multiple scientific and technical fields.

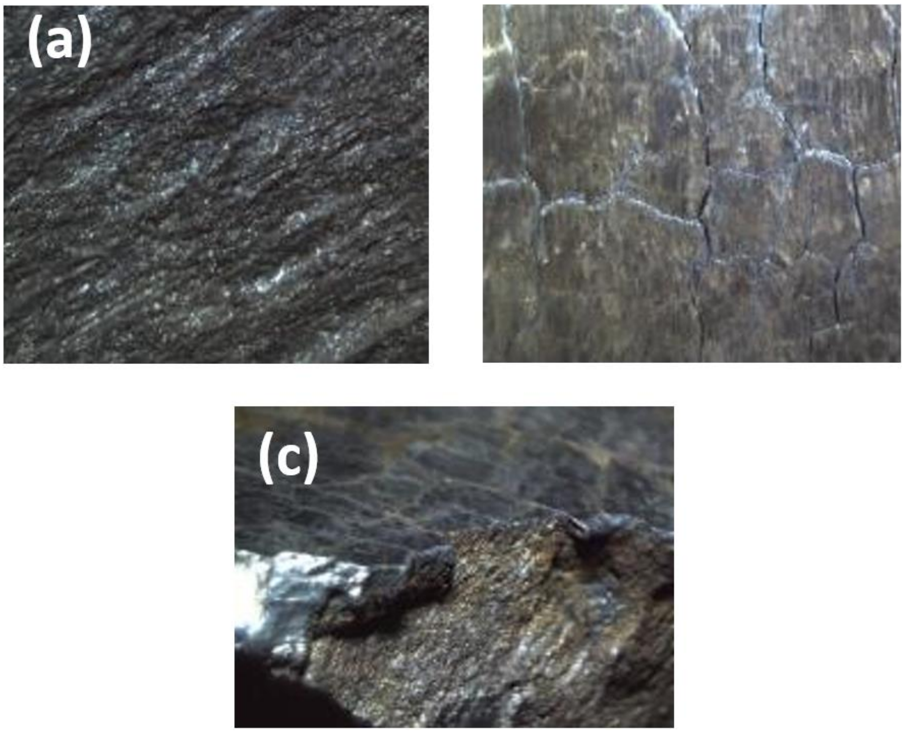

Fig. 4. *Beach marks visible on the fracture surface (a); Prominent fire cracks observed all around the rolling face of roller guide (b); Separation (fracture) found to be occurring along fire crack planes (c)*

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3.5. Optical microscopy

The cross-sectional sample was polished up to 1500-grit emery paper, followed by 1 µm velvet cloth polishing, and then etched using a 2% nital solution to reveal the microstructures and observe defects. The micro-examination carried out in accordance with ASTM E407 and the ASM Handbook, Volume 9.

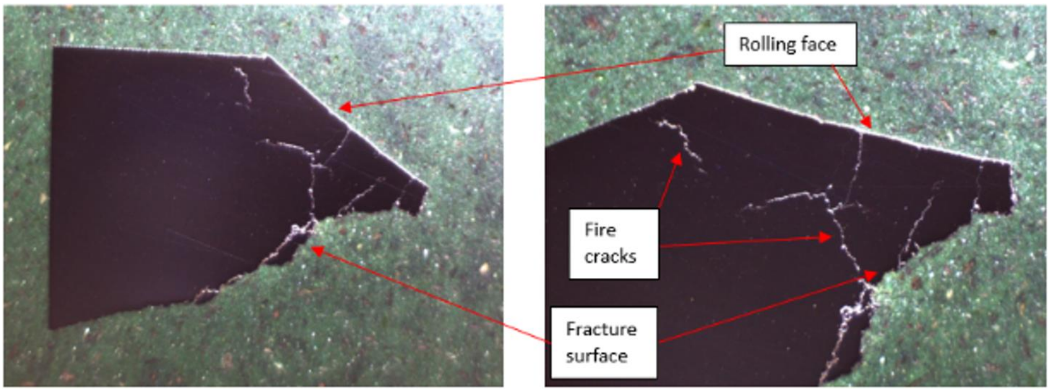

Fig. 5. *OM observation points*

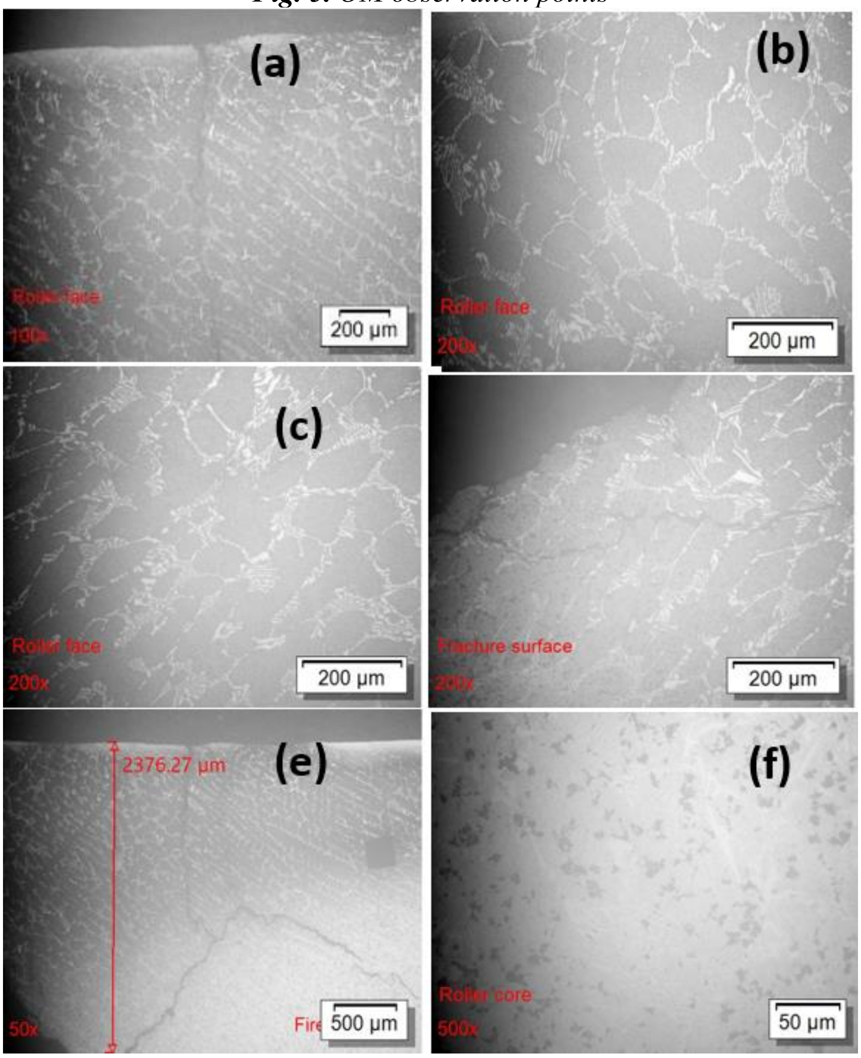

Fig. 6. *OM microstructures, (a) Roller face Micro-image, (b) Fire cracks can be seen, (c) Roller face region, (d) Micro-image, Depth of fire crack > 2.376 mm*

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Micro-examination (Figures 5 and 6), conducted according to ASTM E407 and the ASM Handbook Volume 9, follows industry best practices for metallurgical analysis. The process ensures accurate and repeatable results for material characterization, quality control, and failure investigation.

The sample was hot-mounted with phenolic resin. After proper grinding and polishing, the sample was subjected to inclusion analysis using optical microscopy. Inclusions were evaluated using micrographic analysis according to the ASTM E45 standard. The inclusion rating was performed under a light microscope with a 100x objective. After inclusion analysis, the sample was etched with 2% nital. The etched sample was examined to check for the presence of a decarburized layer or to determine if any case hardening had been applied to the component.

The sample was found to have higher sulphide inclusions on the order of 2.0 (thin series). It was fairly clean and free from any harmful inclusions / exogenous entrapment. No surface hardening was found to have been given to the part. The hardness and microstructures were homogeneous throughout the sample. Because surface hardening gives better fatigue life. Metallographic examination revealed a homogeneous microstructure throughout the roller guide cross-section. There was no indication of surface hardening treatments such as induction or flame hardening. The uniform hardness profile suggests the part was likely used in a normalized or cold-drawn condition. Surface hardening techniques are known to significantly improve fatigue life, especially in components subjected to cyclic or torsional stresses like roller guides.

Inclusion Analysis ASTM E45, Method A: ASTM E45 is a standard test method for determining the inclusion content in steel using microscopic examination. It is primarily used in quality control and material certification to ensure the steel meets required cleanliness standards.

ASTM E45 categorizes inclusions into the following main types: 1. Type A (Sulfide Inclusions) – Usually manganese sulfides (MnS), elongated due to rolling. 2. Type B (Aluminate Inclusions) – Alumina (Al_2O_3) inclusions, typically globular. 3. Type C (Silicate Inclusions) – Elongated silicates, formed from deoxidation.

Material Cleanliness: The sample was found to be fairly clean, with no evidence of harmful non-metallic inclusions or exogenous entrapments that could contribute to premature failure. This indicates proper steelmaking practices and material quality.

3.6. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) were carried out on the cross-sectional fractured surface of the sample to observe the surface morphology and identify the elements present on the surface.

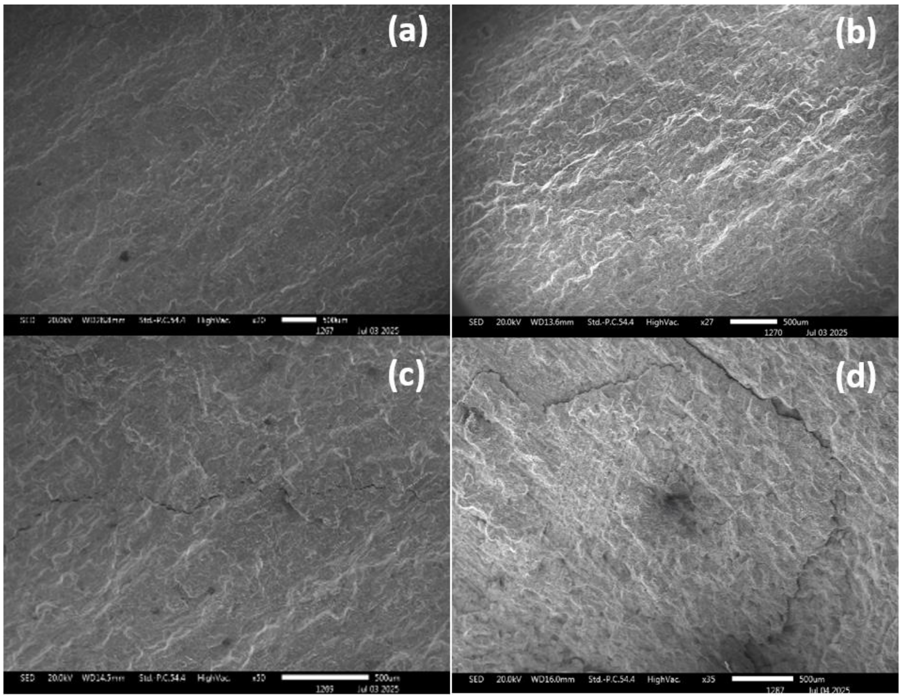

Fig. 7. *SEM micrographs, (a and b) beach marks crack propagation, (c) secondary cracks, (d) fatigue crack initiation*

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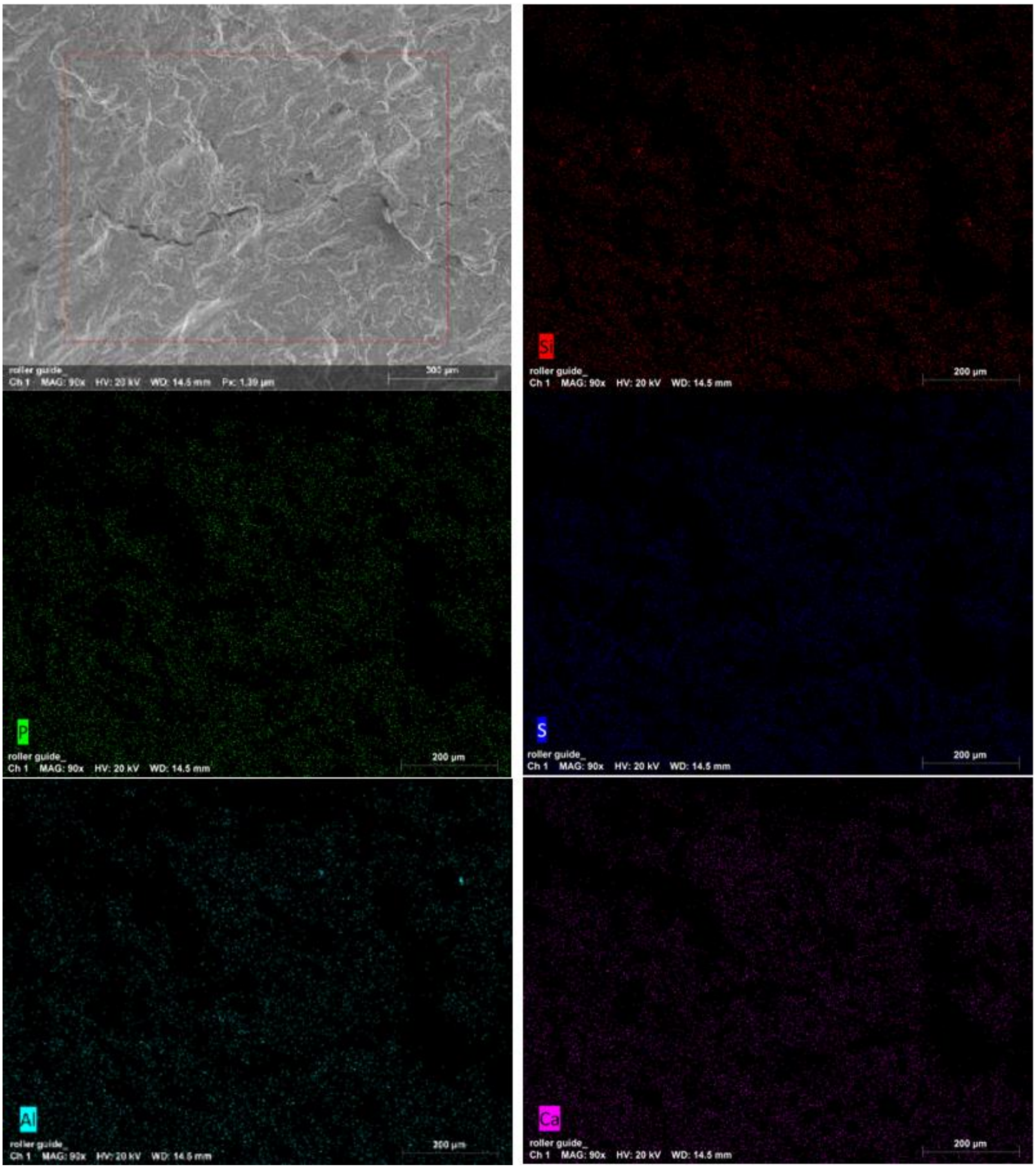
A typical intergranular fractured surface was revealed throughout the sample (Figure 7). This fracture surface displays a characteristic intergranular fracture mode, meaning the cracks propagated along grain boundaries rather than through the grains themselves. The distinctive features visible are individual grains with well-defined boundaries, revealing how the fracture paths preferentially followed these boundaries.

Evident outlines of individual grains indicate that the separation occurred along grain boundaries, suggesting grain boundary weakness. The sharp edges suggest that minimal deformation occurred during the fracture, which is consistent with a brittle fracture mode.



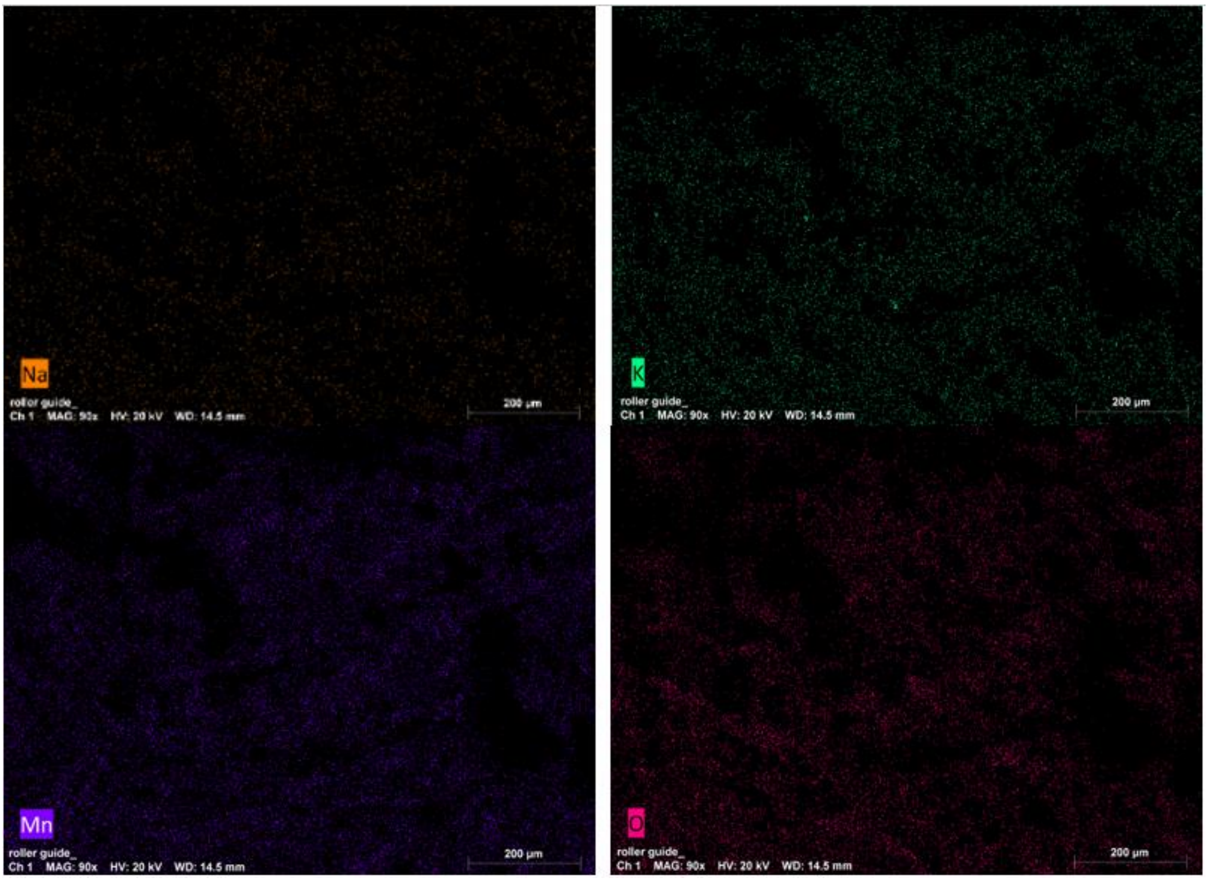


Fig. 8. *EDS mapping of the chemical element distribution*

3.7. Energy dispersive X-ray spectroscopy (EDS)

As suggested by the arrangement of the elemental distribution on the EDS map (Figure 8), the intergranular fracture surface reveals a homogeneous dispersion of alloying elements.

4. Conclusions

In summary, the comprehensive analysis of the roller guide failure sample has provided substantial insights into the mechanisms underlying its failure, pointing toward a fracture produced by fire cracks on the rolling face of the guide rolls. Thermally induced surface cracks are typically caused by rapid and repeated heating and cooling cycles during rolling operations, leading to localized thermal fatigue.

The guide rolls, which are in direct contact with high-temperature steel, are typically well protected from fire cracks and thermal fatigue through a combination of material selection, design features, surface treatments, and operational controls. These factors ensure roll life durability, minimize downtime, and prevent catastrophic roll failure in the rolling line process.

ASTM A 681-D2 Tool Steel is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium as per the ASTM A 681 standard. It is the most widely used steel among the group D steels due to its abrasive wear resistance, high compressive strength, good through-hardening properties, high stability during hardening and good resistance to tempering. In the same standard ASTM A 681 – D3 grade is defined with a similar chemistry pattern; however, the key difference is the absence of Molybdenum and Vanadium. These 2 elements make a significant difference when using rolls in repeated heating and cooling cycles during rolling operations.

We conclude that the root cause of the failure is identified as the use of an inadequate steel grade for manufacturing the guide rolls operating under repetitive heating and cooling cycles. As a result, the guide rolls experienced pronounced fire cracking, which progressively developed into thermal fatigue damage, ultimately leading to catastrophic failure and a high disruption of the rolling process.

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