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Investigation of Failure Factors for Sidewalls in Pallet Cars of Pelletizing Factory Furnaces

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Abstract

This research investigates the causes of premature failure in side walls of pelletizing furnace wagons (pallet cars) operating at high temperatures. The sidewalls are manufactured from HH-type heat-resistant stainless steel (DIN 1.4837, X40CrNiSi25-12). Despite expected resistance to high-temperature oxidation and thermal shock, these components experience premature failure within 3-6 months of service. Through field inspections, microstructural characterization, mechanical testing, chemical analysis, and thermal gravimetric analysis, this study identifies the primary failure mechanisms. Results indicate that the continuous chromium carbide (Cr_{23}C_6) layer formed along austenite grain boundaries during solidification is the main cause of embrittlement and reduced impact resistance. Additionally, the presence of oxide and carbonitride inclusions, microporosity, and possible spinodal decomposition in the austenite phase contribute to mechanical property degradation. The studied steels do not meet minimum impact energy requirements per HH-type II standards. This research provides recommendations for post-casting heat treatment and alloy modification to enhance service life.

Keywords:

Sidewall, Pelletizing Cars, HH-type stainless steel, Chromium carbide, Premature failure, High-temperature oxidation

1. Introduction

Pelletizing plants utilize furnace wagons (pallet cars) that transport iron ore pellets through high-temperature indurating furnaces reaching up to 1300°C. The side walls of these wagons, known as sidewalls, are critical components directly exposed to hot gas flows, thermal cycling, and corrosive atmospheres containing CO, CO₂, and sulfur compounds. These components are manufactured from HH-type heat-resistant stainless steel, specified as DIN 1.4837 (X40CrNiSi25-12) with 24-28% Cr and 11-14% Ni. According to ASTM A447-11, this steel is available in two types: HH-type I (ferritic-austenitic) and HH-type II (fully austenitic).

In the Gol Gohar Sirjan pelletizing plant, sidewalls experience unexpected premature failure within 3-6 months of installation, significantly shorter than their design life. This premature failure causes production stoppages, pressure drops in the furnace, and damage to refractory linings. Despite manufacturer claims of adequate high-temperature performance, the actual service life indicates underlying metallurgical issues.

Previous research has identified various degradation mechanisms in heat-resistant steels, including oxidation, carburization, sulfidation, internal oxidation, and dusting phenomena. However, the specific failure mechanisms affecting Iranian-manufactured HH steel sidewalls under actual operating conditions require comprehensive investigation. This study aims to identify the root causes of premature failure through systematic characterization of both new and service-exposed sidewalls from two domestic suppliers.

2. Methodology

Field inspections were conducted on sidewalls from multiple pallet cars over eight months, with damage classified into five quality levels based on visual appearance. Level 5 represents excellent condition (similar to new), while Level 1 indicates severe oxidation and fracture.

Mechanical testing included tensile testing according to ASTM E8/E8M using an STM-50 testing machine, Charpy impact testing per ASTM A370, and Brinell hardness measurements. Chemical composition analysis was performed using spark emission spectrometry (quantometry) following ISO/IEC 17025 standards.

Microstructural characterization employed optical microscopy at 200× and 1000× magnifications after etching with glyceric acid solution. Scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) was used for detailed phase analysis and identification of inclusions and carbide precipitates.

Thermal gravimetric analysis (TGA) was conducted from 25°C to 1350°C at a heating rate of 30°C/min under atmospheric pressure to evaluate oxidation behavior and identify phase transformations. Samples were collected from three categories: new sidewalls from Supplier 1, new sidewalls from Supplier 2, and service-exposed (failed) sidewalls.

Results and Discussion

3.1. Field Inspection and Damage Distribution

Visual inspection revealed non-uniform damage distribution along the sidewalls. Quality classification showed that approximately 50% of sidewalls fell into categories 2-3 (visible deformation with or without cracking). Severe oxidation and cracking (Level 1) were observed predominantly at upper edges in direct contact with hot gas flow. Statistical analysis indicated that right-side walls experienced slightly more severe degradation than left-side walls, possibly due to asymmetric gas flow patterns in the furnace.

3.2. Mechanical Properties

Tensile testing results showed that new sidewalls from both suppliers exhibited yield strengths (230-250 MPa) and ultimate tensile strengths (510-530 MPa) within acceptable ranges. However, impact testing revealed critical deficiencies: all samples showed impact energies significantly below the minimum requirement of 150 J specified in relevant standards. Supplier 1 steel showed impact energy of 25-28 J, while Supplier 2 steel showed 23-25 J. Service-exposed samples exhibited further reduction to approximately 15 J, indicating severe embrittlement during operation.

Hardness values ranged from 190-200 HB for new samples and increased slightly in service-exposed samples (200-210 HB). The substantial reduction in impact toughness while maintaining tensile strength suggests that embrittlement mechanisms operate at the microstructural level rather than through surface oxidation alone.

3.3. Chemical Composition

Quantometry analysis confirmed that both steels fall within the HH-type category. Supplier 1 steel contained 0.36% C, 1.25% Si, 1.16% Mn, 24.79% Cr, 0.33% Ni, with detectable Mo (0.19%), Cu, Nb, V, and Ti. Supplier 2 steel contained 0.42% C, 1.83% Si, 0.90% Mn, 24.59% Cr, 11.54% Ni, with significantly lower Mo (0.09%) but notable nitrogen content.

The higher nitrogen in Supplier 2 steel (confirmed by EDS detection of nitride inclusions) represents an economic substitution for more expensive nickel as an austenite stabilizer. However, nitrogen combined with strong nitride-forming elements (Ti, Al, V) promotes formation of brittle nitride and carbonitride inclusions that degrade impact toughness.

Using the Schaeffler diagram, both steels were determined to be fully austenitic (HH-type II) with Cr-equivalent/Ni-equivalent ratios of approximately 0.7, indicating zero ferrite content. This eliminates sigma phase embrittlement as a primary failure mechanism.

3.4. Microstructural Characterization

Optical metallography revealed significant microstructural differences between suppliers. Supplier 1 steel exhibited elongated dendritic grains, indicating high pouring temperature or rapid cooling during solidification (possibly due to high thermal conductivity mold sand). Supplier 2 steel showed more equiaxed grain structure.

Critically, both steels displayed continuous carbide networks along austenite grain boundaries. SEM-EDS analysis identified these as chromium carbides ($Cr_{23}C_6$) containing approximately 80% Cr. This continuous grain boundary carbide

layer is the primary cause of embrittlement, providing preferential crack propagation paths and reducing impact toughness.

Supplier 1 steel contained NbC carbides (white phase in micrographs), confirming niobium addition for grain growth control during high-temperature service. Supplier 2 steel lacked niobium but contained numerous nitride and carbonitride inclusions. Both steels exhibited significant microporosity and oxide inclusions, further degrading mechanical properties.

Service-exposed samples showed no significant change in grain boundary carbide morphology but revealed additional microstructural features within austenite grains, including possible spinodal decomposition products and fine precipitates. High-magnification SEM images suggested lamellar structures indicative of spinodal decomposition in austenite, potentially contributing to embrittlement during prolonged high-temperature exposure.

3.5 Thermal Gravimetric Analysis

TGA results revealed distinct oxidation behavior among samples. All samples exhibited initial weight loss between 400-500°C, corresponding to chromium carbide oxidation ($\text{Cr}_{23}\text{C}_6 + \text{O}_2 \rightarrow \text{Cr}_2\text{O}_3 + \text{CO}$). Supplier 1 and service-exposed samples showed more pronounced weight loss in this region, while Supplier 2 showed gradual weight loss from 250-600°C.

Following initial carbide oxidation, samples achieved relative stability until approximately 1100°C, where rapid oxidation commenced due to protective oxide layer breakdown. This temperature represents the alloy's "surrender point" to oxidation. Service-exposed samples showed compromised protective layer formation, suggesting pre-existing damage to the oxide scale during service.

The inflection observed around 475°C in all samples correlates with known embrittlement phenomena. While 475°C embrittlement typically occurs in ferritic and duplex stainless steels via spinodal decomposition of ferrite, the fully austenitic structure of these steels suggests possible analogous transformations in austenite, consistent with the microstructural observations [1-5].

3.6 Failure Mechanism Synthesis

The collective evidence indicates that premature sidewall failure results from multiple interacting factors:

1. **Primary Cause:** Continuous grain boundary chromium carbide (Cr_{23}C_6) network formed during solidification due to alloy segregation. This brittle phase provides preferential crack paths and reduces impact toughness below minimum standards even in new components.
2. **Contributing Factors:** Microporosity, oxide inclusions, and nitride/carbonitride inclusions (particularly in nitrogen-alloyed steel) further degrade mechanical properties and serve as stress concentration sites.
3. **Service-Induced Degradation:** Prolonged high-temperature exposure promotes:
 - Internal oxidation via oxygen diffusion along grain boundaries
 - Potential spinodal decomposition within austenite grains (475°C embrittlement analog)
 - Progressive carbide coarsening and associated chromium depletion zones
 - Cyclic thermal stresses causing crack initiation at brittle grain boundaries
4. **Oxidation Behavior:** While protective Cr_2O_3 layers form initially, thermal cycling and mechanical stresses cause spallation, exposing fresh metal to oxidizing atmospheres. The chromium-depleted zones adjacent to grain boundary carbides cannot reform protective oxide, accelerating localized oxidation and crack propagation.

The absence of sigma phase formation and unchanged sulfur/carbon levels in service-exposed samples rules out sulfidation and sigma phase embrittlement as dominant mechanisms, confirming that as-cast microstructure quality and subsequent metallurgical transformations are the critical factors.

3. Conclusions

This investigation reveals that premature failure of HH-type stainless steel sidewalls in pelletizing furnaces primarily results from continuous grain boundary chromium carbide networks formed during solidification, which cause severe embrittlement and impact toughness below minimum standards even in new components. Contributing factors include

microporosity, oxide inclusions, and nitrogen-induced carbonitride precipitates, while service exposure promotes internal oxidation and possible spinodal transformations that further degrade mechanical properties. Neither domestically produced steel meets quality requirements, necessitating post-casting homogenization heat treatment to eliminate continuous carbides and alloy modifications with niobium and molybdenum to enhance high-temperature performance and service life.

4. References

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