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REVIEW OF THE POTENTIAL APPLICATIONS OF SURFACTANTS IN METALLURGY: FROM ORE BENEFICIATION TO FINISHED PRODUCT PROCESSING

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Annotation:

The article examines the multifaceted role of surfactants (surface-active agents, SAA) in metallurgical processes, highlighting their amphiphilic properties that reduce surface tension at phase interfaces, enabling applications in ore extraction, pellet production, agglomeration, smelting, and finished product processing. In ore beneficiation, surfactants enhance flotation, dispersion, and separation, improving mineral recovery while reducing energy and reagent use, though their efficiency depends on ore type and process conditions.

In pelletizing, they improve particle dispersion, pellet strength, and binder efficiency but risk excessive foaming and environmental concerns due to low biodegradability.

During agglomeration and smelting, surfactants enhance material uniformity, slag flowability, and impurity removal, yet pose challenges like toxic emissions and dosing complexity.

In product processing, surfactants improve cleaning, pickling, coating, and corrosion protection, but residues and toxicity complicate their use. The article emphasizes the need for biodegradable surfactants and advanced wastewater

treatment to mitigate environmental and economic drawbacks while optimizing metallurgical efficiency.

Keywords: surfactants, surface tension, amphiphilic structure, ore beneficiation, froth flotation, pelletizing, agglomeration, smelting, impurity removal, surface cleaning, pickling, coating, biodegradable surfactants, environmental risks, energy efficiency, wastewater treatment, process optimization.

1. Introduction

Surfactants, or surface-active agents (SAA), are chemical compounds capable of significantly reducing surface tension at phase interfaces, such as liquid-gas, liquid-solid, or liquid-liquid. Due to their amphiphilic structure, comprising hydrophilic and hydrophobic components, surfactants form micelles, emulsions, foams, and dispersions. Their primary property is adsorption at phase boundaries, which influences wettability, emulsification, and system stability [1].

Surfactants are widely used in household chemistry as the basis for detergents, ensuring wetting and stain removal.

In cosmetics, they serve as emulsifiers, stabilizers, and foaming agents, with sodium lauryl sulfate in shampoos and lecithin in creams as typical examples. In the food industry, surfactants act as stabilizers in emulsions (sauces, chocolate, ice cream), while in pharmaceuticals, they form the basis of ointments, act as drug carriers, and serve as disinfectants. In agriculture, surfactants enhance leaf wetting by pesticides and herbicides, improving their efficacy.

In industry, surfactants are applied in oil extraction, construction, textile production, and environmental remediation, improving mixture flowability, fabric wetting, and pollutant dispersion.

In metallurgy, surfactants play a critical role across all stages, from raw material preparation to final product finishing, facilitating phase separation, pelletizing, charge stabilization, energy efficiency, and enhancing the quality and durability of metal products.

2. Surfactants in Ore Extraction and Preparation

During froth flotation for ore beneficiation, surfactants are pivotal in separating valuable minerals from gangue by altering surface wettability [2]. The main surfactant groups in flotation include:

- **Collectors**: Selectively adsorb onto mineral surfaces, increasing hydrophobicity and promoting attachment to air bubbles.
- **Frothers**: Stabilize foam, ensuring effective mineral flotation.
- **Modifiers**: Regulate medium properties, such as pH, and influence process selectivity.

In ore preparation, surfactants are used to disperse particles in pulp, facilitating grinding and classification. They also enhance particle separation in magnetic or gravity separationprocesses.

Advantages of Surfactant Use: Improved recovery of valuable components, reduced energy and reagent consumption, optimized chemical processes, and enhanced beneficiation quality.

Disadvantages of Surfactant Use:

a) **Technological Limitations**: Surfactants must be selected based on ore type, as incorrect choices reduce efficiency. Their performance depends on process conditions (pH, temperature, pulp mineralization), and excess residues can complicate water recycling.

b) **Economic Aspects**: Some surfactants are costly, increasing overall beneficiation expenses. Additional costs arise from treating surfactant-containing wastewater.

c) **Environmental Risks**: Certain surfactants are toxic and pose threats to aquatic ecosystems. Residues may accumulate in tailings and leach into the environment, with synthetic surfactants often exhibiting low biodegradability, exacerbating ecological concerns.

3. Surfactants in Pellet Production.

Pellets are spherical granules (10–14 mm) made from crushed iron ore concentrate through pelletizing for use in blast furnace production. Surfactants are employed during raw material preparation and granule formation to enhance pellet properties and process efficiency [3].

- Raw Material Preparation: Surfactants are added to iron ore pulp to disperse particles and prevent agglomeration, improving mixture flowability. Examples include polyacrylamides and carboxymethylcellulose. Surfactants also enhance particle wetting with water, ensuring better adhesion during pelletizing, often using non-ionic surfactants like fatty alcohols.

- Pellet Formation: Surfactants are added to binders (e.g., bentonite) to ensure uniform distribution, increase the strength of green pellets, and control porosity, which is critical for gas permeability during firing. Lignosulfonates, as typical modifiers, can enhance raw pellet strength by 10–20% and reduce binder consumption to 0.5–1% of concentrate mass. Surfactants also improve pellet size uniformity, reducing transportation losses.

Advantages: Up to 20% increase in pellet strength, optimized binder consumption, and improved product quality and uniformity.

Disadvantages:

- **Technological**: Excess surfactant dosing may cause excessive foaming, reduced granule strength, or undesirable reactions with binders. Precise dosing is critical, as over-concentration alters pulp rheology and complicates pelletizing.
- **Economic**: Specialized surfactants, such as polyacrylamides or fatty alcohols, increase production costs. In some cases, their use may not yield expected quality improvements, questioning economic viability.
- **Environmental**: Some surfactants do not fully decompose during firing, affecting slag chemistry and emission levels. They also enter process wastewater, requiring additional treatment. Low biodegradability of certain compounds (e.g., polyacrylamides) complicates waste disposal.

Thus, surfactant use in pellet production offers technological benefits but involves economic and environmental risks. Increasingly, biodegradable surfactants based on natural fatty acids and advanced wastewater treatment systems are employed to mitigate negative impacts.

4. Surfactants in Agglomeration and Blast Furnace Production

During raw material preparation for pig iron and steel smelting – crushing, agglomeration, pelletizing, and charge formation – surfactants enhance the physicochemical properties of materials, facilitating efficient blast furnace operation [4].

Crushing: surfactant dispersants reduce pulp viscosity during wet grinding, improving particle separation efficiency. For instance, lignosulfonates minimize agglomeration in mills. Surfactants also enhance surface wettability during magnetic or hydrocyclone separation, improving mineral separation.

Agglomeration: surfactants improve wetting of charge components, ensuring robust granule formation. Non-ionic surfactants (e.g., polyethylene glycol) enhance the mechanical strength of raw agglomerates, while reduced surface tension promotes uniform moistening and improves gas permeability.

Charge Preparation: surfactants modify the surface properties of ore, coke, and fluxes, enhancing mixture uniformity. Cationic surfactants reduce dust formation during transportation, while surfactant addition to fluxes improves their dispersion in the charge, aiding impurity removal (e.g., sulfur, phosphorus).

Advantages: 10–15% increase in agglomerate strength, reducing transportation losses; lower water and energy consumption due to improved dispersion; enhanced charge uniformity and smelting stability.

Disadvantages: Precise dosing is required to avoid excessive foaming or reduced agglomerate strength; additional costs for surfactants and wastewater treatment; potential impact of surfactant residues on slag composition during smelting.

5. Surfactants in Pig Iron and Steel Smelting.

Although less common in blast furnace and steelmaking processes than in raw material preparation, surfactants play a vital role in enhancing phase interactions (metal, slag, gas) and optimizing impurity removal [5].

Pig Iron Smelting (Blast Furnace): Surfactants may be added to fluxes or directly into the blast furnace to reduce slag surface tension, improving its flowability and facilitating sulfur and phosphorus removal. Examples include fluorine-containing surfactants or silicates. Non-ionic surfactants may treat coke to enhance wettability and heat transfer. In some configurations, surfactants stabilize foam in the slag formation zone, improving furnace gas dynamics.

Steel Production (Converter and Electric Arc Furnace): Surfactants reduce slag viscosity and enhance impurity removal efficiency. Cationic surfactants stabilize slag emulsions, while at high temperatures, they promote fine-dispersed metal-slag emulsions, accelerating chemical reactions. In continuous casting, surfactants are incorporated into mold fluxes to reduce surface tension and improve lubrication, preventing metal adhesion to the crystallizer.

Advantages: 20–30% reduction in sulfur content due to improved slag formation; 5–10% lower energy consumption due to enhanced slag flowability; improved billet quality in continuous casting.

Disadvantages: Fluorine-containing surfactants may produce toxic emissions (fluorides), requiring environmental controls; high cost of specialized high-temperature surfactants; dosing complexity, as excess causes foaming and process instability; unburned surfactant residues may affect metal or slag composition.

Thus, surfactants enhance technological parameters in both raw material preparation and smelting, improving dispersion, agglomerate strength, energy efficiency, and impurity removal. However, their use requires careful consideration due to environmental impacts, high costs, and technological challenges.

6. Surfactants in Finished Product Processing.

At the final stage of metallurgical production, surfactants are used in cleaning, pickling, coating, lubrication, and preparation of products for storage or transportation [6]. Their wetting, dispersing, and emulsifying properties enhance metal surface quality.

Surface Cleaning: Surfactants are components of cleaning solutions for removing oils, scale, and dust from steel and cast iron products. Sodium lauryl sulfate is effective in detergents for hot-rolled products. In ultrasonic cleaning, surfactants reduce surface tension, aiding penetration into micropores.

Pickling: In acidic pickling baths, surfactants enhance wetting, ensuring uniform oxide removal and reducing acid consumption. Ethoxylated alcohols prevent gas bubble formation, which hinders uniform pickling.

Coating Application: Surfactants stabilize electrolytes in galvanic processes (e.g., cationic quaternary ammonium compounds), improving coating adhesion. In paint and polymer systems, polyacrylamides act as dispersants and stabilizers, ensuring uniform application.

Lubrication and Protection: Surfactants are included in lubricants and anti-corrosion agents applied to finished products to reduce friction and protect against corrosion. Fatty acids are used in temporary protective coatings. In cold rolling, surfactants in emulsions reduce equipment wear.

Transportation Preparation: Non-ionic surfactants in wax compositions form a thin film, reducing dust formation and contamination during storage.

Advantages: Improved surface quality and product durability; reduced material consumption (acids, electrolytes, paints); corrosion protection during storage.

Disadvantages:

- **Technological**: Surfactant residues may impair coating adhesion, requiring thorough rinsing; effectiveness depends on temperature, pH, and concentration; potential unwanted interactions with coating components.
- **Economic**: High cost of specialized surfactants (e.g., fluorine-containing); increased wastewater treatment costs after cleaning and pickling.
- **Environmental**: Synthetic surfactants (alkylphenols, fluorine-containing compounds) are toxic and poorly biodegradable; surfactant use in paints may generate volatile organic compound emissions; residues in sludges complicate waste disposal.

Thus, surfactants are critical in finished product processing, enhancing cleaning, pickling, coating, and corrosion protection. They improve surface quality and reduce material costs but involve technological challenges (residues, condition dependence), high costs, and environmental risks. The industry addresses these by adopting biodegradable surfactants and advanced wastewater treatment methods.

7. Key Development Directions and Challenges of Surfactant Use in Metallurgy

Key development directions include expanding the use of biodegradable surfactants; integrating surfactants across all metallurgical stages, from beneficiation to coating; optimizing energy consumption and charge stability; improving wastewater treatment systems; and reducing costs through enhanced wettability and reagent distribution.

Key challenges include: 1) **Technological**: Difficulty in selecting and dosing surfactants, dependence on medium parameters, and residual effects on metal surfaces, complicating further coating. 2) **Economic**: High cost of specialized surfactants, expenses for wastewater treatment, and sludge disposal. 3) **Environmental**: Toxicity of certain surfactants, low biodegradability, water and soil contamination, and formation of volatile harmful compounds.

Conclusions:

Surfactants are essential in metallurgical production, applied in beneficiation, pelletizing, agglomeration, smelting, and product processing. They enhance process efficiency, reduce resource consumption, and improve metal product quality. However, their use requires a balanced approach due to technical, economic, and environmental risks. A promising direction is the adoption of eco-friendly biodegradable surfactants and advanced waste and water treatment systems.

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