eISSN: 2229-3213
pISSN: 2229-3205
The Journal of Applied Science and Social Science
Volume 16,Issue 06
June, 2026

IMPACT OF STEEL GRINDING MEDIA–INDUCED IRON CONTAMINATION ON FLOTATION PERFORMANCE OF VARIOUS ORES

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https://doi.org/10.5281/zenodo.20612582

Abstract: The influence of steel grinding media on flotation performance is strongly governed by iron contamination generated during wet milling. This study synthesizes experimental findings from six peer-reviewed investigations to evaluate how abrasion-, corrosion-, and precipitation-derived iron species alter pulp chemistry, mineral surface properties, and flotation responses across multiple ore types, including sulphide ores, scheelite, and PGM-bearing ores. Results demonstrate that steel grinding media significantly reduce pulp potentials (Eh) and dissolved oxygen (DO), promoting the formation of Fe^{2+}/Fe^{3+} species and iron hydroxide coatings on mineral surfaces. SEM–EDS and XPS analyses consistently reveal extensive FeOOH and $Fe(OH)_3$ deposition, particularly on fine particle fractions, resulting in suppressed collector adsorption and decreased hydrophobicity. Comparative flotation data show that mild steel produces the lowest recoveries for chalcopyrite, scheelite, and PGM minerals, while ceramic and chromium-rich media substantially improve selectivity and overall recovery. Integrating these outcomes confirms that iron contamination is the dominant chemical mechanism reducing flotation efficiency in steel grinding environments, highlighting the need for optimized media selection to enhance metallurgical performance.

Keywords—Steel grinding media, iron contamination, pulp chemistry (Eh, DO), surface oxidation, collector adsorption, flotation performance

PO'LAT YANCHISH JISMLARI KELTIRIB CHIQARADIGAN TEMIR IFLOSLANISHINING TURLI RUDALARNI FLOTATSIYALASH KO'RSATKICHLARIGA TA'SIRI

Annotatsiya. Po'lat yanchish jismlarining flotatsiya samaradorligiga ta'siri, asosan, ho'l yanchish jarayonida yuzaga keladigan temir ifloslanishiga bog'liq. Ushbu tadqiqot oltita taqrizdan o'tgan ilmiy ishlarning eksperimental natijalarini umumlashtiradi hamda yemirilish, korroziya va cho'kindi shaklidagi temir birikmalarining sulfidli rudalar, sheelit va tarkibida PGM (platina guruhi metallari) bo'lgan rudalarda pulpa kimyosini, mineral yuzasi xususiyatlarini va flotatsiya reaksiyalarini qanday o'zgartirishini baholaydi. Natijalar shuni ko'rsatadiki, po'lat yanchish jismlari pulpa potensialini (Eh) va erigan kislorod (DO) miqdorini keskin pasaytiradi, bu esa mineral sirtida Fe^{2+}/Fe^{3+} birikmalari hamda temir gidroksidi qoplamalarining hosil bo'lishini jadallashtiradi. SEM–EDS va XPS tahlillari shuni ishonchli tarzda tasdiqlaydiki, ayniqsa, mayda zarrachali fraksiyalarda FeOOH va $Fe(OH)_3$ ning keng ko'lamli cho'kishi kuzatiladi va bu kollektor adsorbsiyasining susayishiga hamda gidrofoblikning pasayishiga olib keladi. Qiyosiy flotatsiya ma'lumotlariga ko'ra, yumshoq po'lat xalkopirit, sheelit va PGM minerallarini ajratib olishda eng past ko'rsatkichlarni namoyon qiladi, keramika va xromga boy jismlar esa selektivlik va umumiy ajratib olish darajasini sezilarli darajada yaxshilaydi. Ushbu natijalarning umumlashtirilishi shuni tasdiqlaydiki, po'lat yanchish muhitida flotatsiya samaradorligini pasaytiruvchi asosiy kimyoviy mexanizm temir ifloslanishi hisoblanadi va bu metallurgik ko'rsatkichlarni yaxshilash uchun yanchish jismlarini to'g'ri tanlash zarurligini ko'rsatadi.

Kalit so‘zlar: Po‘latni silliqlash muhiti, temir bilan ifloslanish, bo’tanani kimyosi (eh, do), yuza oksidlanishi, kollektor adsorbsiyasi, flotatsiya samaradorligi

Introduction

The grinding environment plays a decisive role in determining the flotation behavior of sulphide and oxide minerals. During comminution, steel grinding media undergo electrochemical wear, releasing dissolved and colloidal iron species (Fe^{2+}, Fe^{3+}, $FeOOH$, $Fe(OH)_3$) into the pulp. These species adsorb onto mineral surfaces, altering surface charge, hydrophobicity, dissolution rates, and collector adsorption mechanisms. As documented by Peng and Grano (2010), iron contamination is particularly detrimental for fine particles (<10 µm), where enhanced oxidation and adsorption of iron hydroxides greatly reduce floatability, especially of galena and chalcopyrite [1,7].

Beyond particle size sensitivity, the extent of iron contamination is strongly influenced by grinding conditions—particularly wet milling, galvanic interactions, dissolved oxygen depletion, and pH-dependent hydrolysis reactions. In wet grinding systems, the steel–sulphide galvanic couple accelerates anodic dissolution of iron, while sulphide minerals such as chalcopyrite and pyrite act as cathodic sites, promoting rapid formation of hydrophilic ferric oxyhydroxide films. These physicochemical changes shift the pulp environment toward lower redox potentials, suppressing xanthate chemisorption and significantly altering froth phase behavior.

Recent studies broaden this understanding across other mineral systems. Yao et al. (2020) demonstrated that cast-iron grinding balls significantly reduce scheelite recovery, producing rough, Fe-coated surfaces that suppress collector adsorption [2]. Similar iron-induced depression effects were observed for chalcopyrite in both copper and polymetallic ores, where steel media produce low redox potentials, oxygen depletion, and hydrophilic surface films [3–5]. In contrast, inert media—ceramic, stainless steel, or high-chromium alloys—produce cleaner surfaces, higher dissolved oxygen, more favorable pulp potentials, and improved flotation performance [2,4,6,8].

Furthermore, the chemical environment generated during grinding not only affects sulphide flotation reactions but also influences entrainment, slime coating, and pulp rheology, particularly in complex multicomponent systems. Studies on PGM-bearing ores report that steel media can increase chromite entrainment and depress fine PGM recovery, whereas inert media preserve mineral hydrophobicity and reduce slime coating effects, highlighting mineralogical dependency in media selection [6-9].

Despite extensive research, the cross-comparison of iron-induced contamination effects across different ore types (sulphides, scheelite, PGM ores) remains limited. Most studies investigate individual mineral systems or specific grinding environments, leaving a gap in understanding how universal or ore-specific these mechanisms are. Understanding these mechanisms across mineral systems is essential for optimizing grinding circuits and selecting proper grinding media for improved beneficiation.

Thus, this study aims to systematically synthesize literature findings to evaluate how steel grinding media–derived iron contamination affects flotation kinetics, pulp chemistry, mineral surface reactivity, and separation efficiency across various ore types. By integrating mechanistic insights across multiple mineral systems, the work seeks to provide a unified framework that clarifies when and why steel-induced iron contamination leads to poor flotation performance and how alternative grinding media can mitigate these effects.

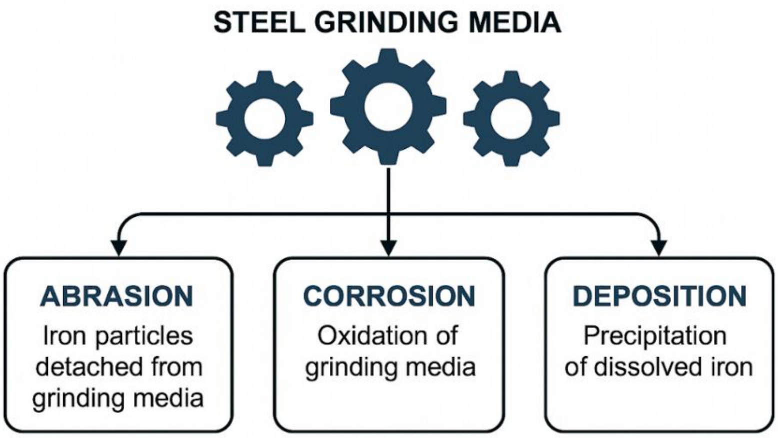

Fig. 1. Conceptual illustration of iron contamination mechanisms from steel grinding media during wet milling

1. MATERIALS AND METHODS

This research is based on a comparative and systematic synthesis of experimental procedures reported in six peer-reviewed studies investigating the influence of steel grinding media on mineral flotation performance. Although each study focuses on different ore types (sulphides, scheelite, copper–pyrite, and PGM ores), their methodologies share common principles regarding sample preparation, grinding environments, pulp chemistry evaluation, surface analysis techniques, and flotation testing. The following subsections summarize the core methodological approaches.

1.1 Mineral Samples and Ore Characteristics

The reviewed studies examined multiple mineral systems affected by iron contamination:

- Galena and chalcopyrite: high-purity samples from Broken Hill and Mount Oxide mines, crushed to 0.6–3.2 mm feed size [1-10].
- Scheelite ($CaWO_4$): high-grade pure mineral sourced from China, ground to <75 µm for flotation tests [2-12].
- Copper sulphide ores: containing chalcopyrite, pyrite, covellite, and chalcocite, representative of industrial milling circuits [3,5].
- PGM-bearing UG2 ore: highly disseminated chromite-rich ore (<15 µm PGM grain size) used to evaluate media effects on fine particle flotation [6-13].

Initial mineralogy and purity were verified through X-ray diffractometry (XRD) and chemical composition analyses (ICP-AES, ICP-MS), depending on the study.

1.2 Grinding Media Types and Compositional Variables

All studies compared steel grinding media with low-reactivity or inert alternatives:

Grinding Media Type	Composition / Characteristics	Referenced Studies
Mild Steel (MS)	~100% Fe; high corrosion rate	[1], [4], [5], [6]
Cast Iron Balls (CIB)	Fe + FeO + FeOOH contamination tendency	[2]
Chromium Steel (15–30% Cr)	Reduced Fe dissolution	[1], [5]
Stainless Steel (SS)	Corrosion-resistant, inert	[5], [6]
Ceramic / Nano-Ceramic Media	Al_2O_3-based, inert	[2], [4], [6]

Grinding media masses ranged from 4 kg (laboratory mills) [1] to full-scale ball mixtures (15–25 mm balls) in 3 L Denver flotation circuits [5].

Specific surface areas of grinding media were determined by geometric measurements to quantify relative corrosion exposure [1].

1.3 Grinding Procedure and Pulp Chemistry Control

Grinding was conducted in wet or dry environments depending on study objectives:

Wet Grinding Conditions

- Pulp densities ranged 60–67% solids [5,6].
- Grinding duration was controlled to achieve:
- P80 < 75 µm for sulphide ores [5]
- 90% < 53 µm for single minerals [1]
- pH during grinding was adjusted and maintained at pH 9.0 using NaOH or HCl [1,4].
- Gas purging:
- N_2 for reducing environments
- O_2 / air for oxidizing conditions [1]

Dry Grinding Conditions

Used mainly for comparison of redox effects:

- No galvanic interaction with water
- Higher rest potentials and surface activation were observed [5]

1.4 Flotation Testing Procedure

Flotation experiments were conducted using standardized laboratory configurations:

Flotation Cells and Conditions

- 1.5 L flotation cell for single mineral flotation [1, 12]
- 40 mL microflotation cell for reagent sensitivity evaluation [4]
- 3 L Denver DR-12 cell for copper–pyrite ore flotation [5]
- 8 L batch cell for PGM ore tests [6]

Airflow rates: 2.5–7 L/min

Impeller speeds: 1200–1992 rpm

Collector reagents:

- Xanthate-based collectors (SIBX, PAX, isobutyl xanthate) [4–6]
- Dithiophosphate (DTP) and Diisobutyldithiophosphinate (DBPhos) [1]

Frothers: Dowfroth 250, pine oil [1,4,5]

Collector adsorption was allowed for 1–3 min, with flotation times up to 20 minutes.

1.5 Particle Size Classification and Size-by-Size Analysis

To examine iron contamination effects on fine particles:

- Wet sieving at 45 µm to separate fine/intermediate fractions.
- Cyclone separation (CS1–CS7 fractions) for particle size profiling (2–32 µm range).
- 200- and 400-mesh sieving used for chalcopyrite/pyrite fractioning [4].

These methods quantified the susceptibility of fine particles to oxidation and iron deposition.

1.6 Electrochemical and Surface Characterization Techniques

Investigated parameters included:

Electrochemical Measurements

- Rest potential (Eh) using Ag/AgCl reference electrodes
- Continuous monitoring of:
- Eh (mV, SHE-scale)
- Dissolved oxygen (DO) (ppm)
- pH evolution [5,6]

Surface Analytical Tools

- SEM–EDS: surface morphology + Fe coating detection [1,2,4]
- XPS: oxidation state mapping (Fe^0, Fe^{2+}, Fe^{3+}, S^{-2}/S^0) [2,4]
- ToF-SIMS: surface secondary ion distribution on sulphides [1]

- UV–Vis spectrophotometry: collector adsorption quantification [4]
- Zeta potential measurements: surface charge response to iron contamination [2]

1.7 Data Interpretation and Cross-Study Comparative Approach

This paper adopts a structured comparison framework:

- Grinding media → Fe contamination intensity
- Pulp chemistry (Eh, DO, pH) → Mineral oxidation behavior
- Surface coatings (FeOOH, FeOx) → Collector adsorption mechanisms
- Particle size dependence → Floatability loss
- Ore-specific responses (sulphide, scheelite, PGM)

The standardized approach allows mechanistic comparison across ore types despite differing experimental setups.

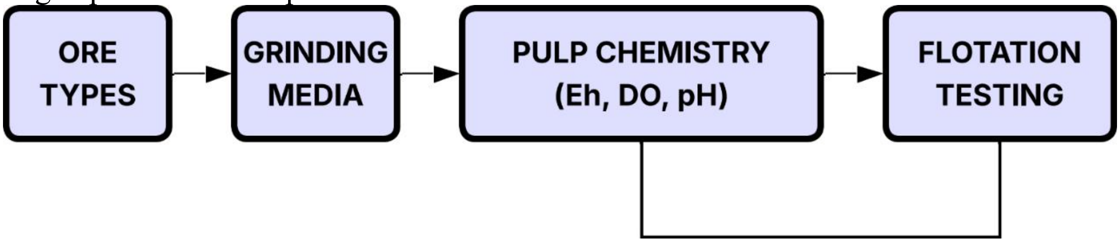

Fig. 2. Experimental workflow used to assess how different grinding media influence pulp chemistry and flotation outcomes.

2. RESULTS AND DISCUSSION

2.1 Iron Contamination and Its Effect on Pulp Chemistry

A central finding across studies is that steel grinding media cause significant dissolution and oxidation of iron, generating Fe^{2+}, Fe^{3+}, FeOOH, and $Fe(OH)_3$ species in the pulp. These species accumulate more rapidly under wet grinding conditions.

2.1.1 Redox Potential (Eh) Depression

- Mild steel produces the lowest pulp potentials, reaching –300 to –400 mV during wet grinding [5].
- Such reducing conditions suppress collector adsorption on sulphide minerals, particularly xanthates, which require moderately oxidizing environments.
- Stainless steel and ceramic media maintain significantly higher Eh values (–50 to +150 mV), favoring flotation [3,6].
- These observations confirm Peng & Grano's (2010) conclusion that iron contamination fundamentally modifies pulp chemistry to the detriment of sulphide flotation [1].

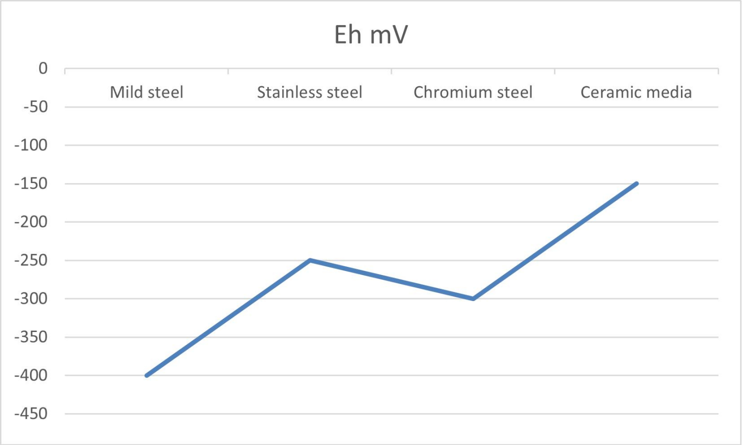

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Fig. 3. Comparison of pulp potentials (Eh) under different media conditions.

2.2 Dissolved Oxygen (DO) Consumption and Galvanic Effects

Steel grinding media create strong galvanic interactions:

- Iron acts as the anode, dissolving rapidly.
- Sulphide minerals (chalcopyrite, pyrite) act as cathodes.
- Oxygen reduction reactions dramatically decrease dissolved oxygen levels.

For example:

- DO in scheelite slurry: 8.36 ppm (ceramic) → 5.14 ppm (cast iron) [2].
- DO in Cu–pyrite slurries dropped to near 0 ppm during wet MS grinding [5].

Low DO levels correlate with:

- decreased collector adsorption,
- increased mineral oxidation,
- and poorer flotation selectivity.

2.3 Mineral Surface Modification by Iron Species

2.3.1 SEM–EDS Observations

All studies employing SEM–EDS reported clear Fe contamination:

- In scheelite flotation, CIB-ground particles were covered with FeO/FeOOH patches, while ceramic-ground surfaces remained clean [2].
- Peng & Grano (2010) observed similar Fe-rich coatings on galena and chalcopyrite, especially in particles <10 µm [1].
- Liao et al. (2020) confirmed iron-oxide layers formed on chalcopyrite under steel grinding, reducing hydrophobicity [4, 10].

2.3.2 XPS and ToF-SIMS Findings

Surface analyses revealed:

- increased Fe^{3+} species (FeOOH, Fe_2O_3) under steel grinding;
- formation of oxidized sulphur species on sulphides;
- inhibited collector attachment due to competitive adsorption.

These effects were strongest in fine particles, which have higher surface area and oxidation rates [1].

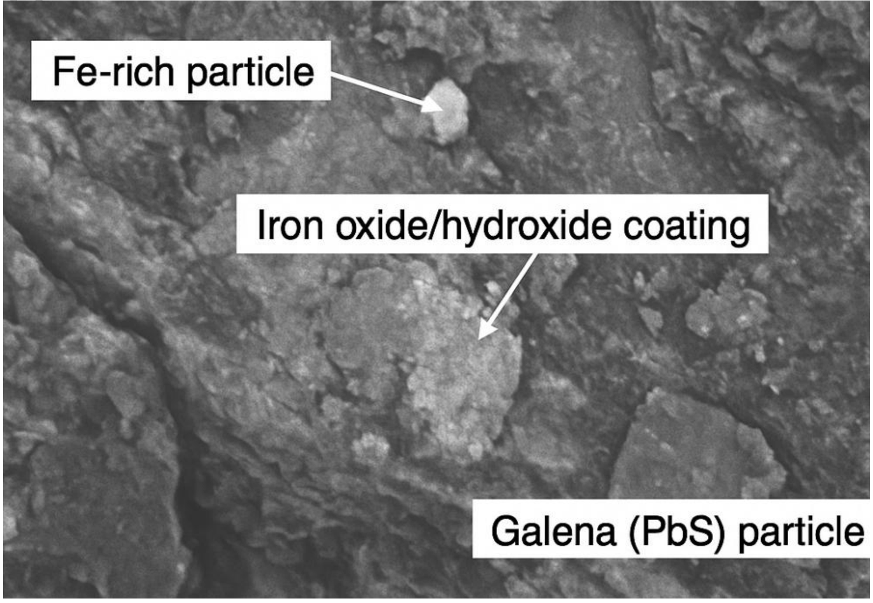

Fig. 4. SEM evidence of Fe contamination on mineral surfaces under steel grinding.

2.4 Influence on Collector Adsorption

Xanthate adsorption is strongly suppressed by iron hydroxides:

- Liao et al. (2020) showed significantly lower isobutyl-xanthate adsorption on steel-ground chalcopyrite versus nano-ceramic ground samples [4].
- FeOOH coatings create positively charged sites → electrostatic repulsion with anionic collectors.

Yao et al. (2020) found that Fe contamination increased Ca^{2+} release from scheelite due to dissolution, further decreasing collector performance [2].

2.5 Particle Size–Dependent Effects

Fine particles (<10 µm) consistently show the greatest sensitivity to iron contamination:

- Peng & Grano demonstrated near-complete depression of fine galena and chalcopyrite under mild steel grinding [1].
- PGM ores showed lower recovery of fine platinum-group minerals when steel was used, mainly due to entrainment displacement and surface contamination [6].

Mechanism:

- Fine particles oxidize faster.
- Their high specific surface area increases Fe adsorption.
- They require stronger hydrophobicity, which is suppressed by iron films.

Thus, steel media disproportionately harms fine-particle flotation.

2.6 Flotation Performance Across Different Ore Types

2.6.1 Sulphide Minerals (Galena, Chalcopyrite, Pyrite)

- Iron contamination depresses chalcopyrite and galena.
- Pyrite may show slight activation under some reducing conditions, but selectivity decreases sharply [4,5].

2.6.2 Scheelite ($CaWO_4$)

- Steel media cause significant Fe contamination → reduces NaOl (oleate) adsorption → decreases grade and recovery [2].

2.6.3 Copper–Pyrite Ores

- Wet MS grinding produced worst separation efficiency: high pyrite recovery → poor Cu grade [5,8].

2.6.4 PGM Ores (UG2)

- Ceramic media → highest PGM recovery, lowest chromite entrainment.
- Stainless steel → lowest PGM recovery due to strong Fe-surface interactions [6].

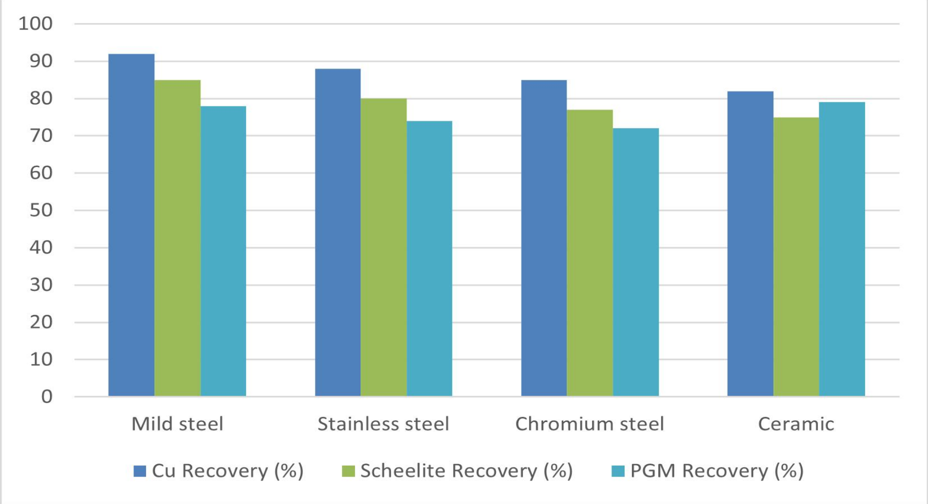

Fig. 5. Summary comparison of flotation recoveries under different grinding media for multiple ore types.

2.7 Mechanistic Interpretation

Across all studies, the following universal mechanisms were confirmed:

1 Steel media produce Fe hydroxides/oxides → surface fouling
2 Pulp potential decreases → suppresses collector adsorption
3 DO consumption increases → slows xanthate chemisorption
4 Fine particles accumulate more iron species

5 Overall flotation recovery decreases, especially for sulphide minerals
6 Inert media reverses all negative effects, producing:

- higher recovery,
- better selectivity,
- higher grade,
- improved flotation rates.

The combined evidence demonstrates that iron contamination is the dominant chemical mechanism controlling flotation performance in steel media grinding environments, confirming the conclusions of Peng & Grano (2010) and extending them across additional ore systems.

3. CONCLUSION

This study comprehensively analyzed the impact of steel grinding media–induced iron contamination on the flotation performance of various ore types, drawing on six peer-reviewed experimental investigations. Despite differences in mineralogy, flotation reagents, and grinding conditions, a consistent set of detrimental chemical and surface-based mechanisms were observed across sulphide ores, scheelite, and PGM-bearing ores.

The results reveal that steel grinding media significantly alter pulp chemistry, generating highly reactive Fe^{2+}/Fe^{3+} species and iron hydroxides that rapidly adsorb onto freshly ground mineral surfaces. These species decrease redox potential, suppress dissolved oxygen levels, and compete with collectors for adsorption sites, leading to severe depression of mineral hydrophobicity. Surface analytical techniques (SEM-EDS, XPS, ToF-SIMS) consistently demonstrated the formation of FeO, FeOOH and $Fe(OH)_3$ coatings on steel-ground particles.

A critical finding across all studies is the strong particle-size dependence of iron contamination effects: fine particles (<10 μm) accumulate thicker oxide layers, undergo faster surface oxidation, and show markedly reduced flotation recoveries, especially in chalcopyrite, galena, and PGM-rich fractions. This highlights the sensitivity of ultrafines to galvanic corrosion and their vulnerability to steel-induced surface fouling.

Across different ore systems, the consequences are universal:

- Sulphide minerals (galena, chalcopyrite) show major recovery losses under steel grinding.
- Scheelite experiences reduced collector adsorption due to Fe-induced surface dissolution and contamination.
- Copper–pyrite ores suffer from decreased selectivity and pyrite “mis-activation” under reducing conditions.
- PGM ores ground with steel show the lowest PGM recovery and highest chromite entrainment.

Conversely, inert grinding media (ceramic, nano-ceramic, stainless steel, high-chromium alloys) consistently produced cleaner mineral surfaces, higher pulp potentials, improved collector adsorption, and significantly enhanced flotation performance.

Overall, the synthesis clearly demonstrates that iron contamination is the dominant chemical mechanism controlling flotation behavior in steel media grinding, and that replacing steel with inert media provides substantial metallurgical benefits across mineral systems. These insights have important implications for optimizing industrial grinding circuits, particularly in operations targeting fine particle recovery and high selectivity.

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