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Exploration of genetic characteristics of flake graphite mineral processing and prediction of process indexes

Yanping Niu [1,2], Yameng Zhang [1], Sen Cheng [1]

[1] College of Mining Engineering, Heilongjiang University of Science and Technology, Harbin 150022, Heilongjiang, China
[2] State Key Laboratory of Mineral Processing Science and Technology, Beijing 100160

Corresponding author: niuyanping2004@126.com (Yanping Niu)

Abstract: This paper establishes the connection between the characteristics and selectivity behavior of scaly graphite deposits, ores, and minerals from a genetic perspective, and predicts the process indicators. This study explores the relationship between the genetic characteristics of flaky graphite deposits and their mineral processing behavior. Samples from 8 graphite-producing areas in the Jiamusi-Xingkai graphite metallogenic belt were analyzed with the aim of predicting key technological indexes. First, systematic process mineralogy research was carried out. The structural characteristics, chemical composition, mineral composition and particle size distribution, graphite monomer liberation degree, graphite flake size and gangue mineral inclusion between graphite layers were analyzed in detail using techniques such as electron microscopy, the automated quantitative mineral analysis system (MLA), scanning electron microscopy, and the alkali fusion method for graphite flake size determination. In combination with data on ore deposit genesis, beneficiation tests, and production practices, a comparative analysis was performed to identify the genetic characteristics that affect graphite selectivity. These include the degree of metamorphism of the ore deposit, the weathering degree of the ore, the particle size distribution of graphite, and the intergrowth relationships between graphite and typical minerals (such as those prone to slimes, easy-to-float minerals, and flaky minerals). Additionally, a preliminary prediction of concentrate grade and recovery rate was made, and a set of predictive rules for the process flow was established, which aligns with the actual process parameters.

Keywords: flake graphite, mineral processing technology, mineralogical characteristics, index prediction, liberation degree

1. Introduction

China's famous mineral processing expert, Academician Sun Chuanyao, proposed the concept of "gene mineral processing engineering", suggesting that the genesis of deposits, ore properties, and mineral characteristics are closely related to selectivity, exhibiting a form of "inheritance" that makes these factors decisive in the beneficiation process and its performance indicators (Sun et al.,2018). The genesis of the deposit determines ore structure, mineral compositions, and crystallization sizes, which subsequently influences mineral embedding relationships and ore selectivity. The structural characteristics of the ore directly affect the difficulty of the monomer dissociation of the target minerals in the process of ore crushing and grinding, which in turn affects the flotation separation of the minerals. Mineral genes refer primarily to the crystal-chemical characteristics of minerals and other physical genes, which directly determine the surface characteristics of minerals, and thus affect the flotation of minerals (Yin et al.,2021)

Global graphite is used in refractory, casting and lubrication industries, accounting for 75% of the total consumption, while strategic emerging fields such as new energy vehicles and new materials account for 25% of the consumption (Liu et al.,2019). As of 2022, the global reserves of natural graphite resources are about 330 million tons, and the identified reserves of natural graphite in China are 92.698 million tons, of which 87% are crystalline graphite (Liu et al.,2024), mainly distributed in Heilongjiang, Inner Mongolia, Xinjiang, Sichuan, Shandong and other provinces. Heilongjiang Province alone has

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super-large crystalline graphite mining areas with reserves reaching 10 million tons, including the Yunshan graphite deposit in Luobei, the 260 Highland graphite deposit in Luobei, the Northwest Ling-Sanhecun crystalline graphite deposit in Linkou County, and the Xigou crystalline graphite deposit in Shuangyashan (Yan et al., 2023). The Luobei area has emerged as the largest graphite production base in China (Zhang et al., 2014).

The weathering degree, mineral composition, and graphite embedding particle size of graphite ore have a significant impact on the grinding and flotation processes. For graphite ores with a high content of large flakes, a stage grinding and flotation process that protects the flakes is required (Xu et al., 2024), along with a pre-screening stage for large flakes to separate them from the gangue in a timely manner and avoid the grinding and flotation of fine-flake graphite (He et al., 2023; Wang et al., 2024). Sun et al. (2017) used a rod grinding and pre-screening process for weathered graphite ore in Africa, where some clay minerals were mixed between graphite layers, resulting in a significant increase in the content of large flakes in the final concentrate. For fine-flake graphite deposits, directly increasing the coarse grinding strength and improving the liberation degree of graphite monomers. Ma et al. (2023 conducted a mineralogical study on fine-flake graphite ore in Luobei and found that the interlayer distribution of flake graphite and muscovite made graphite sorting challenging. Some graphite minerals and gangue were distributed in a fine-grained impregnated state in the ore, leading to a low flotation concentrate grade. The use of ultrasonic pretreatment technology can effectively improve the flotation performance of fine-flake graphite (Tong et al., 2024; Zhou et al., 2023; Barma et al., 2019). Ultrasound-modified kerosene improves its dispersibility, thereby enhancing the flotation efficiency of graphite (Jiang et al., 2024). Additionally, the addition of certain inorganic electrolytes can significantly improve the flotation effect of graphite (An et al., 2022). Compared to diesel, kerosene can effectively reduce the entrainment of mica and quartz in the graphite concentrate (Qiu et al., 2022). The use of nano bubble flotation technology can enhance the adsorption effect of collectors, improve the collision and adhesion performance between graphite particles and bubbles, significantly reduce the number of flotation stages for fine-flake graphite, and significantly improve the grade and recovery rate of fine graphite (Zhang et al., 2023; Li et al., 2024; Tang et al., 2023; Ma et al.,2022). In addition, after chemical purification of graphite flotation concentrate, the fixed carbon content can be increased to nearly 99% (Sinha et al., 2014).

This paper targets crystalline graphite ores in the Jiamusi-Xingkai (land mass) graphite orogenic belt as the research subject. It investigates the relationship between the genetic characteristics of graphite deposits, ores, and minerals, and their corresponding beneficiation process flows. The study explores methods for predicting the genetic characteristics and process parameters, providing a foundation for the development of a research system for graphite ore genetic mineral processing engineering.

2. Materials and methods

2.1. Experimental raw materials

The Jiamusi-Xingkai (land mass) graphite mineralization belt is located in the area of Jixi, Luobei, Shuangyashan and Linkou in eastern Heilongjiang Province. First, the production mines in different regions with relatively comprehensive historical data on the genesis of the deposits, the nature of the ores and beneficiation practices are selected as the primary focus. Second, graphite deposits with different flake sizes (large flakes, small and medium flakes, and micro-fine flakes) are selected for analysis.

The study area mainly has six active graphite mines, namely, Pride Liumao Graphite Mine in Jixi City, Puchen Graphite Mine in Jixi City, Changyuan Graphite Mine in Langjiagou of Betray in Jixi City, Yunshan Graphite Mine in Luobei County, Yixiang Graphite Mine in Luobei County, and Zhongshuang Graphite Mine in Shuangyashan City. Due to the lack of micro-fine graphite ore in the produced mines, two unmined extra-large micro-fine scale graphite deposits, Northwest Leng Graphite Mine in Linkou County and 260 Highland Graphite Mine in Luobei County, were added. A total of 8 raw ore samples, 6 flotation concentrate samples, and 2 tailings samples (from Pryde and Yunshan) were collected for graphite genetic characterization. The raw ore samples were collected from graphite ores after on-site mixing and rough crushing operations. The flotation concentrates were taken from the filter press on the production line, and the tailings were collected at the stockpile. Raw ore samples from the two non-producing graphite mines were taken from the bedrock at the bottom of the trenching works.

2.2. Experimental method

2.2.1. Chemical analysis

The main and trace elements were measured separately. Appropriate pretreatment methods were selected based on the sample's composition and matrix, followed by complete digestion of the sample. The subsequent measurements were carried out using the relevant analytical techniques.

2.2.2. Microscopical analysis

The structure, texture, mineral composition, and grain size distribution of the ore were analyzed using a Zeiss Scope.A1 microscope. Thin sections were prepared to observe the embedding characteristics of vein minerals, while polished sections were used to examine the inclusion characteristics of metal minerals. The samples to be tested were ground into light thin slices and observed under the microscope. The thin section was mainly used to observe the embedding characteristics of the vein minerals in the ore, while polished sections were used to study the inclusion characteristics of metal minerals and the grain size distribution of graphite.

2.2.3. SEM analysis

A FEI model 650F scanning electron microscope was used to analyze the morphology and interlayer inclusions of graphite in the samples. The samples were ground to the appropriate particle size, sieved into 3-4 grain size fractions, and then embedded in epoxy resin. After the epoxy resin was applied and the samples polished to prepare them for observation, the surface was sprayed with carbon. The samples were then placed in the scanning electron microscope to examine the mineral composition, embedded particle size, and the content of vein minerals interspersed between the graphite scale layers.

2.2.4. Process mineral automatic quantitative analysis system (MLA analysis)

The mineral composition and content, embedded particle size, degree of liberation, and other related parameters were analyzed. The experiment was conducted using FEI's MLA automatic analysis system in conjunction with an FEI 650F scanning electron microscope. The processed test samples were placed in the scanning electron microscope, where the MLA automatic analysis system was activated for automatic detection. The results were then combined with chemical analysis data to quantitatively assess mineral content.

2.2.5. Acid immersion-alkali melting analysis of raw graphite flake

Acid leaching-alkali melting method was used to remove vein stones and impurities from the -2mm graphite raw ore sample. After fully enriching the graphite, the graphite flake size was screened and analyzed. The main steps are as follows: Soak the sample in a 1:1 concentration hydrochloric acid to remove metal minerals. After washing to neutrality, soak the sample in 50% hydrofluoric acid in a 60°C water bath until no fine impurities remain in the sample. The sample is subjected to flotation, and the flotation concentrate is acid-leached with hydrofluoric acid. The flotation tailings are manually picked to remove impurity quartz particles before acid leaching. The acid-leached concentrate and tailings are mixed evenly. According to the weight ratio of graphite to sodium hydroxide, add sodium hydroxide in a ratio of 1:2, stir well, and place in a 700 ℃ high-temperature furnace for 1 hour of calcination. The alkali melt product is boiled in a beaker for 1 hour, washed twice with 5% concentration hydrochloric acid until neutral, filtered, and dried to obtain high-purity graphite. Measure the diameter of graphite flakes using 30 mesh (550 μ m), 50 mesh (270 μ m), 80 mesh (180 μ m), 100 mesh (150 μ m), and 200 mesh (75 μ m) target sieves, analyze fixed carbon, and convert the distribution of fixed carbon with different graphite flake diameters.

For small flake graphite samples, the Dandong Bettersize 3000 laser particle size analyzer was used to further analyze the distribution of graphite particles with a diameter smaller than 75 μ m.

3. Results

3.1. Chemical analysis of raw ore

Table 1 shows that the fixed carbon content in the eight graphite raw ore samples ranges from 7% to 15%, making it the primary component of interest. The recycling value of other elements is negligible. Among these, the fixed carbon content of Luobei 260 graphite ore reaches the highest 14.80%. The fixed carbon content of Jixi Puchen, Changyuan and Linkou Northwest Leng graphite ores is relatively low at about 7~8%. The fixed carbon content of Luobei Yunshan and Yixiang graphite ores is similar, ranging from 9 to 10%. The fixed carbon content of Jixi Pryde and Shuangyashan Zhongshuang graphite ores is around 11%.

Table 1. Chemical analysis results of graphite raw ore (%)

Graphite mining areas	Fixed carbon	SiO_2	Al_2O_3	TiO_2	CaO	Cu	Fe_2O_3	FeO	K_2O	MgO	Na_2O	P_2O_5	S	V_2O_5	LOS
Jixi Pryde	11.60	50.83	8.58	0.483	12.31	0.0077	2.14	2.58	2.00	2.48	0.21	0.18	1.84	0.118	15.66
Jixi Puchen	7.59	55.74	11.20	0.677	4.71	0.0082	5.25	1.34	3.72	2.31	0.36	0.163	2.2	0.096	11.9
Jixi Changyuan	8.03	62.08	11.24	0.7	3.28	0.0078	3.58	1.78	1.98	1.9	0.78	0.234	1.52	0.098	11.48
Luobei Yunshan	9.20	51.01	10.76	0.632	9.59	0.0071	1.40	4.19	2.85	4.29	0.37	0.194	2.13	0.069	12.08
Luobei Yixiang	9.81	64.46	10.43	0.579	2.84	0.0025	1.87	0.73	3.55	1.07	0.33	0.08	0.32	0.061	12.36
Luobei 260	14.80	56.53	10.60	0.652	3.11	0.011	2.76	0.75	3.49	1.4	0.22	0.154	0.053	0.103	19.64
Linkou Northwest Leng	7.72	62	14.67	0.858	0.42	0.0066	5.86	0.38	2.99	1.24	0.21	0.138	0.024	0.061	11.6
Shuangyashan Zhongshuang	10.6	44.93	8.21	0.411	16.32	0.0052	3.02	0.92	1.69	1.58	0.36	0.196	0.14	0.091	20.8

3.2. Graphite FLAKE diameter analysis of raw ore

According to Table 2, the content of +100 mesh (greater than 150 μm) large flake graphite varies across the samples: the Jixi Pryde, Puchen, and Changyuan mines have a graphite flake diameter distribution of more than 50%; the Luobei Yunshan graphite mine reaches 40%; and the Luobei Yixiang mine only 20%. The graphite flake diameter in the Luobei 260 and Linkou Northwest Leng graphite mines is mostly below 100 mesh. The Shuangyashan Zhongshuang graphite mine has only 10% of +100 mesh large flake graphite, while -200 mesh (less than 75 μm) graphite content accounts for 65%, classifying it as small flake graphite ore.

Table 2. Cumulative analysis results of graphite flake diameter by acid leaching, alkali melting and screening method (%)

Flake diameter/mesh (μm)	**Pryde**	**Puchen**	**Changyuan**	**Yunshan**	**Yixiang**	**Zhongshuang**	**Northwest Leng**	**Laobei 260**
+30（550）	1.27	1.03	1.63	0.91	0.00	0.00	0.00	0.00
+50（270）	16.24	9.28	19.87	9.42	1.79	1.25	0.00	0.93
+80（180）	42.04	32.30	46.58	26.14	10.72	5.30	0.27	2.18
+100（150）	54.14	50.17	59.61	41.95	20.24	10.91	1.78	2.81
+200（75）	79.62	75.60	80.13	64.44	44.05	35.21	14.79	5.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

To further analyze the graphite flake size distribution in the three small flake graphite deposits—Linkou Northwest Leng, Luobei 260, and Zhongshuang—the graphite samples, after acid leaching and alkali melting treatment, were analyzed using the Dandong Biotek Bettersize 3000 laser particle size analyzer. The results are shown in Table 3.

As shown in Table 3, the graphite flake diameter below 20 μm accounts for 50% of the total graphite flake diameter, with particles below 5 μm making up nearly 18% of the graphite flake diameter in the Linkou Northwest Leng graphite deposit. In the Luobei 260 graphite mine, graphite flakes below 20 μm account for 45%, with particles below 5 μm comprising close to 6% of the graphite flake diameter. In the Shuangyashan Zhongshuang graphite mine, graphite flakes below 20 μm account for 20%, and those below 5 μm account for approximately 4% of the total graphite flake diameter.

Table 3. Results of graphite flake diameter analysis by laser particle size analyzer

Particle size/μm	Cumulative distribution rate/%		
	Shuangyashan Zhongshuang	Luobei 260	Linkou Northwest Leng
-0.50	0.00	0.00	0.00
-1.00	0.06	0.00	0.63
-2.00	0.75	0.66	4.05
-5.00	3.35	5.67	17.88
-10.00	8.53	19.21	33.55
-20.00	20.32	45.67	50.01
-45.00	48.84	80.23	71.44
-75.00	77.37	95.51	87.21
-100.00	90.71	99.13	94.54
-200.00	100.00	100.00	100.00

3.3. Analysis of the dissociation degree of the primary ore monomer

The grinding fineness conditions for the monomer dissociation of the first 6 production mines in Table 4 are consistent with the coarse grinding fineness observed in the actual production data presented in Table 6, indicating relatively good monomer dissociation. The grinding fineness for Luobei 260 and Linkou Northwest Leng is coarser than that in Table 6, with the -45μm fraction reaching 80%, and the dissociation degree approaching 80%. It can be seen that the monomer dissociation corresponds with the results of flake diameter analysis. In the case of Jixi Pryde, the grinding fineness is 55%, with a monomer dissociation of 82.88%. For Jixi Puchen, the grinding fineness is 55% for the -150μm fraction, and the monomer dissociation is 84.53%. The grinding fineness for Jixi Changyuan is also 55% for the -150μm fraction, with a monomer dissociation of 86.44%. The graphite distribution size is relatively coarse and easily dissociates in the Pulaid, Puchen, and Changyuan mining areas in Jixi. The grinding fineness for Luobei Yunshan is 70% for the -150μm fraction, with a monomer dissociation of 82.05%. For Luobei Yixiang, the grinding fineness is 75% for the -150μm fraction, and the monomer dissociation is 86.47%. The graphite distribution size of Yunshan and Yixiang graphite deposits in Luobei is coarser and easier to dissociate. The grinding fineness for double grinding in Shuangyashan is 80%, with a monomer dissociation degree of 85.63%. The graphite distribution size in Shuangyashan ore is fine, and it can be effectively dissociated after fine grinding. The grinding fineness for Luobei 260 is -45μm at 80%

Table 4. Analysis results of monomer dissociation of raw ore grinding products

Mining area name /grinding fineness	Jixi Plaid -150μm 55%	Jixi Puchen -150μm 55%	Jixi Changyuan -150μm 55%	Luobei Yunshan -150μm 70%	Luobei Yixiang -150μm 75%	Shuangyashan Zhongshuang -75μm 80%	Luobei260 -45μm80%	Linkou Northwest Leng -45μm80%
Monomer dissociation/ %	82.88	84.53	86.44	82.05	86.47	85.63	82.89	78.11

with a monomer dissociation of 82.89%. For Linkou Northwest Leng, the grinding fineness is also 80% for the -45μm fraction, and the monomer dissociation is 78.11%. The graphite distribution size in the Xilangling and Luobei 260 graphite ores in Linkou is very fine, making dissociation more difficult.

3.4. Analysis of concentrate products

As shown in Table 5, the grade of large flake graphite (above 150 μm) is higher than that of small flake graphite (below 150 μm) within the same mining area. The fixed carbon grade of the concentrate from the six mining areas ranges from 92% to 96%, with the highest quality achieved by Jixi Puchen and Luobei Yunshan, both reaching 96%, while the lowest is observed in Shuangyashan Zhongshuang, which does not attain a high carbon grade. Among the flotation concentrates, the proportion of flakes larger than 150 μm is highest in Jixi Changyuan and Pride, at approximately 25%, followed by Puchen at nearly 15%. Luobei Yunshan and Yixiang each have only about 10%, with medium- and fine-flake graphite containing virtually no particles larger than 150 μm. The common gangue inclusions between the graphite layers in the flotation concentrate primarily consist of muscovite, clay minerals, pyrite, limonite, and other impurities, which directly impact the quality of the graphite concentrate.

Table 5. Product quality of graphite mine flotation concentrate and gangue inclusion between flake

Mining area	Particle size (μm)	Productivity (%)	Fixed carbon grade (%)	Fixed carbon distribution (%)	The inclusion of gangue between graphite flake layers of concentrate
Pryde	+150	23.80	95.24	24.14	Graphite 94%; Muscovite 4%, mostly distributed in the graphite layer; Quartz 2%, mostly connected with graphite.
	-150	76.20	93.47	75.86	
	total	100.00	93.89	100.00	
Puchen	+150	14.97	96.02	14.93	Graphite 96%; The content of Muscovite and biotite is 2%, respectively, mostly distributed in the graphite layer.
	-150	85.03	96.31	85.07	
	total	100.00	96.27	100.00	
Changyuan	+150	26.13	95.34	26.44	Graphite 95%; Muscovite 3%, pyrite 2%, mostly distributed in the graphite layer.
	-150	73.87	93.85	73.56	
	total	100.00	94.24	100.00	
Yunshan	+150	7.85	97.66	7.97	Graphite 96%; Clay minerals 2%, pyrite 1%, limonite 1%, mostly distributed in the graphite layer.
	-150	92.15	96.11	92.03	
	total	100.00	96.23	100.00	
Yixiang	+150	10.17	97.09	10.32	The graphite content is 95%, with more than 4% muscovite distributed between the graphite layers. Quartz, constituting more than 1%, is intergrown with the graphite.
	-150	89.83	95.51	89.68	
	total	100.00	95.67	100.00	
Zhongshuang	+150	1.50	93.64	1.51	Graphite 93%; Muscovite 5%, limonite 2%, mostly distributed in the graphite layer.
	-150	98.50	92.87	98.49	
	total	100.00	92.88	100.00	

3.5. Tailor embedding characteristics

Through the identification of the graphite ore thin sections under the microscope (see Fig. 1 and Fig. 2), it is observed that the graphite particle size in the tailings is very fine. In the double graphite tailings of Shuangyashan, the graphite particles are generally smaller than 10 μm, while in the Jixi Puchen graphite tailings, the graphite particles are typically smaller than 20 μm. Most of the graphite has been separated into individual particles. The primary reason for the failure to select the graphite is its fine particle size.

3.6 Comparison of graphite ore characteristics and processing methods

The data presented in Table 6 indicate that:

1. The genesis types of the six crystalline flake graphite deposits are all sedimentary metamorphic type, primarily consisting of medium-to-high-grade metamorphic rock-type and medium-to-low-grade metamorphic rock-type graphite deposits (e.g., Northwest Leng). The graphite particle size is extremely fine to relatively fine, and the graphite crystal shape is poor, containing some soil-like graphite content.
2. The three graphite samples from Pude, Puchen, and Changyuan in the Jixi area belong to primary ores and require the addition of quicklime to suppress pyrite. The content of+150 μ m large flake graphite exceeds 50%. The production process uses a relatively low coarse grinding intensity (-150 μm 55%) and a staged grinding flotation process designed to protect the larger flakes. This results in graphite concentrates with a high proportion of +150 μ m flakes, a fixed carbon grade of 94-96%, and a recovery rate of 85-87%.
3. The graphite production areas of Luobei Yunshan and Yixiang are characterized by primary and semi-weathered ores, respectively. The +150 μm large flake graphite accounts for 40% and 20%, respectively. These areas employ a moderate coarse grinding strength (-150 μm 70%) and a staged grinding flotation process, achieving a fixed carbon grade of 95-96% and a recovery rate of 89%
4. The concentrate sample from the Shuangyashan double graphite production area is derived from semi-weathered ore, with fine graphite particle sizes (-150 μ m reaching 98%). The production process uses multi-stage grinding and flotation with a high coarse grinding strength (-75 μ m 80%), resulting in a fixed carbon grade of 93% and a recovery rate of 92%.
5. The graphite samples from Luobei 260 and Linkou Northwest Leng exhibit a strong degree of weathering and contain a large amount of clay-prone minerals, such as kaolinite, chlorite, and limonite. The graphite particles are extremely fine (-20 μ m accounts for 45-50%), and fine grinding is necessary to dissociate the graphite monomers. At the same time, a large amount of secondary sludge is produced, requiring the addition of a large amount of sludge dispersant. As a result, the concentrate achieves a fixed carbon grade of 85-90% and a recovery rate of 75%.

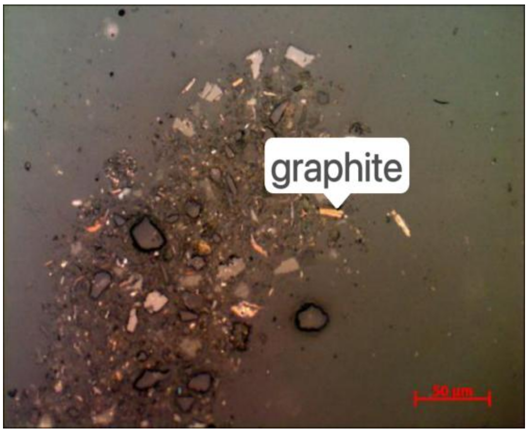

Fig. 1. Shuangyashan double graphite tailings, reflecting light

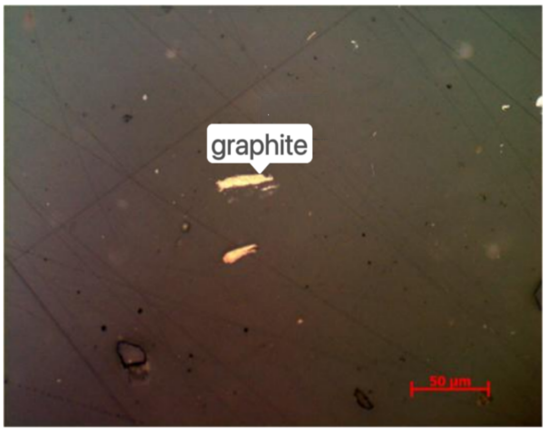

Fig. 2. Graphite tailings of Jixipride, reflecting light

Table 6. Graphite raw ore characteristics and beneficiation process

Meta-morphogenic condition	**Weathering degree Structural construction**	**Mining area**	**Mineral composition (%)**	**Raw ore grade and graphite flake diameter (%)**	**Grinding and flotation process and pharmaceutical regime**	**Product indicators (%)**
Sedimentary metamorphism - medium-high	primary ore. Lamellar flax-like structure Flaky construction,tectonics,infiltrative structure. Scaly granular metamorphic structure,Grainy metamorphic structure.	Pryde	graphite12,quartz28,Pomegranate stone15,Diopside11,feldspar 14,Calcite 6.4,calcite 3.7,kaolinite 2.6,Magnetic pyrite 2,Biotite 1,Tremolite 0.8,Chlorite 0.8,White mica 0.7,serpentine 0.5,sillimanite 0.5,limonite 0.4.	Fixed carbon11.6%; +150μm account 54.14%.	Coarse grinding fineness -150μm 55%;Total amount of medication g/t: quick lime 3000,diesel oil 874,No.2 oil562 。7 grind 10 choices.	Concentrate grade 94; Recovery rate 85; +150μm account 24.
		Puchen	graphite7.6,quartz28,feldspar 26,Biotite 6.6,White mica 6.2,calcite 5.4,Pomegranate stone3.7,Diopside3.7,kaolinite 3,Calcite 3,Chlorite 2,Pyroxene 1,limonite 0.6.	Fixed carbon7.59%; +150μm account 50.17%.	Coarse grinding fineness -150μm 55%;Rough selection of drugsg/t：quick lime 2100,diesel oil 90,No.2 oil40; 9 grind 11 choices.	Concentrate grade 96; Recovery rate 87; +150μm account 15.
		Changyuan	graphite8,quartz41,White mica 10,feldspar 16,kaolinite 4,Pomegranate stone4,calcite 4,Biotite 3,Tremolite 2,Diopside2,Pyroxene 1.4,sillimanite 1,limonite 0.7,Chlorite 0.7.	Fixed carbon8.03%; +150μm account 59.61%.	Coarse grinding fineness -150μm 55%;Total amount of medication g/t: quick lime 2000g/t,diesel oil 800,No.2 oil 300。9 stages grinding and 11 stages flotation.	Concentrate grade 94; Recovery rate 87; +150μm account 26.
		Yunshan	graphite9,quartz24,Diopside 15,feldspar 21,White mica 8.3,Magnetic pyrite 4.8,Calcite 4.6,Biotite 3.2,calcite 2.5,Chlorite 2.2,Pyroxene 1.4,titanite1.4,limonite 0.3.	Fixed carbon9.2%; +150μm account 41.95%.	Coarse grinding fineness -150μm 70%;Total amount of medication g/t: quick lime 1500,diesel oil 800,No.2 oil 200 9grind 11 choices.	Concentrate grade 96; Recovery rate 89; +150μm account 8.
Semi-weathered ore. Massive structure,schistose structure,dipping structure, scale-grained metamorphic structure,accounted structure.		Yixiang	graphite10,quartz42,feldspar 20,White mica 6,Pyroxene 5.3,Pomegranate stone3.7,kaolinite 3.6,Chlorite 3,Diopside 2,Calcite 1.7,calcite 0.6,limonite 0.6.	Fixed carbon9.81%; +150μm account 20.24%.	Coarse grinding fineness -150μm 75%;Total amount of medication g/t： diesel oil 800,No.2 oil 200; 10grind 11choices.	Concentrate grade 95; Recovery rate 89; +150μm account 10.
		Zhongshuang	graphite10.6,quartz23,Calcite 17,Pomegranate stone13.3,feldspar 16.8,Pyroxene 5.5,Tremolite 3.7,kaolinite 2.5,White mica 2.4,Biotite1.5,Chlorite 1,titanite 1,limonite 0.8,calcite 0.3.	Fixed carbon10.6%; +150μm account 10.91%, -20μm 20%, -5μm 4%.	Coarse grinding fineness -75μm 80%;Total amount of medication g/t: diesel oil 1200 ,No.2 oil 1000. 9grind 11 choices.	Concentrate grade 93; Recovery rate 92; +150μm account 1.5.
Weathered ore. Gneiss structure,dipping structure,scale-grained metamorphic structure,accounted structure.		260	graphite15,Potassium feldspar 25,quartz 23,Diopside 9.2,plagioclase 8,kaolinite 9.6,limonite 4.5,Chlorite 0.8,Pomegranate stone2.7.	Fixed carbon14.80%;+150μm account 1.78%, -20μm 45%, -5μm 6%.	Coarse rod grinding-75μm>95%。Rough selection of drugsg/t：kerosene 140,No.2 oil 100,Sodium silicate 2500; 10 times and then grind 11 times, and the ore is broken off and returned.	Concentrate grade 90; Recovery rate 75.
Sedimentary metamorphism - low to medium		Northwest Leng	graphite7.7,quartz41.5,White mica 37.8,limonite 5.5,Chlorite 2.2,Potassium feldspar 2.2,plagioclase 1.	Fixed carbon7.72%; +150μm account 2.81%, 20μm50%, -5μm 18%, -2μm 4%.	Rough grinding-75μm 80%;Rough selection of drugs g/t：Sodium silicate 1000,kerosene 177,No.2 oil 174;1 Rough grinding 3 Rougher concentration, 9 regrind 10 Featured, Middle ore reconcentration dump tail.	Concentrate grade 85; Recovery rate 75; -10μm account 76.

4. Prediction of the process flow and indicator

4.1 Relationship between gene characteristics and process flow

In many graphite deposits, the ore characteristics and mineral properties significantly influence the determination of the beneficiation process and its key indicators, as shown in Table 7.

According to the analysis results of graphite flake diameter, monomer dissociation, beneficiation process and indexes, the judgment rules of grinding system are given, as shown in Table 8.

Table 7. The relationship between graphite gene characteristics and process flow

Genetic characteristics	Influence on the process flow
Degree of deposit metamorphism (medium-high or medium-low)	Grinding Strength, Number of grinding and floating sections
Degree of ore weathering	Rough grinding strength, Dispersant dosage
Particle size of graphite embedding and its embedding relationship with associated minerals (interlayer or encapsulation)	Coarse grinding and regrinding strength, grinding and floating process to protect large scales, dosage of collector and foaming agent
Typical mineral compositions such as easily slaked minerals, easily floated minerals, flake minerals, etc.	Grinding strength, Number of grinding and floating sections, Grinding strength
The inclusion of gangue between graphite flake layers	Number of grinding and floating sections

Table 8. Judgment rules of grinding system

Serial number	Graphite Flake Diameter of Raw Ore (Acid Leach-Alkali Fusion Analysis)	Preliminary assessment of a grinding system	Mining Case
1	+150μm Large scales≥40%	Large scale protection technology: A section of grinding-150μm account 55-70%, Stage grinding again	Jixi Pryde, Puchen, Changyuan, Luobei Yunshan
2	+150μm Large scales<40%, And +75μm mesh Medium to large scales≥40%	Moderate protection of large scales: A section of grinding-150μm account 70-80%, Stage grinding again	Luo Bei Yixiang
3	+75μm mesh Medium to large scales<40%, And +45μm scales≥40%	Increase rough grinding strength, A section of grinding-75μm account 70-80%, Stage grinding again	Shuangyashan Zhongshuang
4	+45μm scales<40%, And -20μm Ultra fine scales≥40%	Increase the intensity of rough grinding: A section of grinding-45μmaccount 70-80%, Stage grinding again	Luobei 260, Northwest Leng

4.2. Preliminary prediction of the process index

4.2.1. Forecast recovery rate

The main factor affecting graphite recovery is the degree of monomer dissociation of graphite. Through the above analysis, it is found that for medium and large flake graphite, in order to protect the graphite flakes, improve product value, and reduce energy consumption, a lower intensity of coarse grinding (single-stage milling) is generally used. Graphite particles smaller than 20 μm, which are wrapped in vein minerals, are difficult to dissociate and are typically lost to the tailings (e.g., Pryde graphite tailings), although their content is relatively small. For micro-fine and ultra-fine flake graphite ores, in order to increase recovery, the intensity of coarse grinding must be increased. In the case of fine and ultra-fine scale graphite ores, to enhance the recovery rate of graphite minerals, it is necessary to increase the degree of monomer dissociation for fine-grained graphite. This generally requires increasing the intensity of coarse grinding; however, due to limitations in grinding equipment and energy consumption concerns, it is very challenging to dissociate graphite particles below 10 μm wrapped in vein minerals (e.g., Zhongshuang graphite mine tailings). Furthermore, some of the dissociated graphite is difficult to recover due to the poor flotation properties of fine-grained graphite. Based on the results presented in Table 3 for graphite flakes smaller than 20 μm or 10 μm, recovery rates can be predicted (see Table 9 for details):

1. Recovery rate = 100% - the percentage content of particles smaller than 20 μm in medium and large flake graphite ores, using a lower grinding strength protective process for the flakes. The portion above 20 μm, where monomer dissociation is achievable, can be fully recovered. The predicted graphite recovery rates for the Jixi Pryde, Puchen, and Changyuan graphite deposits are approximately 90%. For the Luobei Yunshan and Yixiang graphite deposits, the predicted recovery rates are around 87-90%.
2. Recovery rate = 100% - the percentage content of particles smaller than 10 μm in Zhongshuang graphite ore. Although the embedded particle size is fine, by using a higher grinding intensity, monomer dissociation can be achieved for particles larger than 10 μm, which can then be recovered. The predicted graphite recovery rate for Zhongshuang is around 91%. For the Luobei 260 and Linkou Northwest Leng graphite ores, where the embedded graphite particles are fine, increasing grinding intensity enables effective recovery of particles larger than 10 μm. The predicted recovery rates for these ores are approximately 80% and 66%, respectively.

The above recovery predictions are close to the actual process metrics shown in Table 6.

4.2.2. Predicting grade

The main factor affecting the graphite grade is the interlayer inclusion of veinstone within the graphite flakes. As shown in Table 6, the grade of +150 μm large flake graphite is higher than that of -150 μm small flake graphite from the same mine, indicating that a coarser primary particle size of graphite results in a relatively higher concentrate grade. For medium and large flake graphite with a diameter greater than 75 μm accounting for more than 40%, optimizing the beneficiation process can achieve a concentrate grade of 94%-96%. For medium and fine flake graphite, where the diameter greater than 75 μm accounts for less than 40% and the diameter greater than 45 μm exceeds 40%, increasing the grinding intensity can achieve a concentrate grade of 91%-93%. For micro-fine scale graphite, where the content of +45 μm graphite is less than 40% and -20 μm graphite is ⩾ 40%, complete monomer dissociation is difficult, which significantly affects the quality of the concentrate. By optimizing the process, the concentrate grade can reach approximately 85%. The predicted graphite concentrate grade is compared with the actual index in Table 6, and the results are summarized in Table 9. It can be seen from the results of Table 9 that the predicted concentrate grade and recovery indicators are close to the actual indicators.

Table 9. Comparison between predicted indicators of graphite concentrate and actual results

Item/%	Luobei Yunshan	Luo Bei Yixiang	Jinisi Changyuan	Jixi Plaid	Jixi Puchen	Zhongs huang	Luobe i260	Northwest Leng
Predicted grade	94-96	94-96	94-96	94-96	94-96	91-93	85	85
Actual grade	96	95	94	94	96	93	90	85
Predicted Recovery Rate	87-90	87-90	90	90	90	91	80	66
Predicted Recovery Rate	89	89	87	85	87	92	75	75

4.3. Prediction process

The particle size distribution of graphite has been found to exert a significant influence on grinding intensity, the number of grinding-floatation stages, and the dosages of collectors (kerosene or diesel) and frothers (No. 2 oil). Additionally, the presence of associated minerals prone to sliming or those that are easy-to-float has a considerable impact on the selection and usage of modifiers (such as quicklime and water glass) in mineral processing engineering.

The incoming fixed carbon grade of the study mine ranges from 7% to 15%, which has a relatively small impact on the beneficiation process and its associated indices, including the dosage of chemicals. This project preliminarily predicts the graphite ore beneficiation process suitable for this grade (see Figure 3), estimating that the upper limit for the dosages of diesel oil, kerosene, or No. 2 oil corresponds to the 15% fixed carbon grade, while the lower limit corresponds to the 7% grade. The grades of other deposits within this range are predicted to follow a similar pattern based on their respective ratios.

The process judgment is carried out sequentially according to orders 1 through 4: order 1 is executed first, followed by order 2 if the conditions of order 1 are not satisfied, and so on.

For the eight primary study mines in the Jiamusi-Xingkai graphite metallogenic belt, based on the characteristics of the deposits, ores, and mineral genesis as outlined in Table 6, and according to the graphite beneficiation process rules shown in Figure 3, the predicted process is largely in line with the grinding and flotation process, as well as the chemical system for the corresponding deposits, as shown in Table 6.

5. Conclusions

(1) The Jiamusi-Xingkai (tectonic block) graphite mineralization belt is primarily composed of crystalline flake graphite deposits, which belong to the sedimentary-metamorphic type and dominated by medium- to high-metamorphic rock types. Some medium- to low-metamorphic rock-type graphite mines exhibit fine dissemination of graphite, poor crystal morphology, and the presence of some earthy graphite, which negatively impacts their processability. For primary deposits, the addition of quicklime is required during flotation to depress pyrite, while for oxidized deposits, the decision to add a slime dispersant depends on the content of sliming minerals.

(2) The particle size distribution of graphite directly affects grinding intensity, the number of grinding-flotation stages, and the dosage of reagents. The content of associated minerals that are prone to sliming, as well as easy-to-float minerals, influences the selection of modifiers. The mica content and the inclusion of gangue minerals between graphite flake layers affect the number of grinding-flotation stages and have a direct impact on concentrate grade. The degree of liberation of graphite minerals is the primary factor influencing graphite recovery.

(3) The embedded particle size of flake graphite itself is a direct factor affecting the beneficiation process and serves as a basis for predicting the fixed carbon grade and recovery index of the concentrate. The process indexes predicted according to the research method are close to the actual indexes, and the pre-determined process flow rules are consistent with the actual process flow. This study provides a foundational framework for establishing a research system in genetic mineral processing engineering for graphite ores, particularly by linking genetic characteristics of deposits to process optimization and predicting beneficiation outcomes effectively.

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