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Ore Technical Characteristics and Ore Dressing Test of Low Grade Cu-Ni Ore in Huangshan Deposit, NW China

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Abstract: The grade of nickel and copper in Cu-Ni ore, which is the primary sulfide ore in Huangshan deposit in Hami, Xinjiang, is 0.39% and 0.26%, respectively. The dominating metal minerals in it are pyrrhotite, chalcopyrite, pentlandite, magnetite, while gangue minerals are steatite, serpentine, and carbonate. Without depriving steatite prior to mixed-selecting copper and nickel to transfer some suspensible steatite and serpentine into rough concentrate, a series of problems will occur, i.e. the productivity of middling will be high, the efficiency of concentration will be low, the amount of beneficiation reagent will be large, badly exacerbating flotation environment. During metal concentrates some suspensible steatite and serpentine can't be easily suppressed, causing the amount of magnesia high in nickel after separation. To reduce the influence of steatite and serpentine on selecting process, these minerals must be selected out first by good floatability.

***Keywords:** Cu-Ni sulfide deposit, magnesia, low grade, ore dressing experiment, Xinjiang*

1. Introduction

A series of mafic-ultramafic early Permian (~280Ma) intrusions occurs in the Eastern Tianshan and Beishan area[1-3]. Among them are economic magmatic Ni-Cu sulfide deposits, like Huangshan, Huangshandong, Tulaergen, Tianyu and Poyi Etc[4-6]. One key problem is that the grade of Ni and Cu is generally not high, seriously decreasing the economic benefit. The ore dressing technique seems to be of vital importance[7-9]. The Huangshan deposit is a typical example to research the ore technical characteristic of Ni-Cu deposit in these belts. In this paper, we conduct a series of ore dressing methodology and experiments to recognize the ore technical characteristics and ore dressing process of low grade Ni-Cu ore, which may be helpful in the future exploration, ore dressing and metallurgy.

2. Geological Background

Huangshan Ni-Cu deposit locates on the east of Balkhash-Junggar-Hami palaeocontinent, and late Paleozoic Jueluotage rift, on the south of Kangur ductile shear zone. Strata is mainly the uppermost part of the Carboniferous Gandun Formation. Mafic-ultramafic complex forms east-west striking "tadpole shape" on the earth surface, spanning 3.95km in strike with 840m of width on the west and with only 55m of width on the east, accounting for 1.39km^2. It could be divided into 4 intrusion subperiods and 7 petrofacies. Pyrolite forms primitive olivine tholeiitic magma through melt-aggregation during diapiric uprise, emplacing into magma chamber in a certain depth through discordogenic fault. With differentiation and liquation of the magma chamber, coordination of tectonic activity, and multiple emplacements, Cu-Ni sulfide deposits related to mafic-ultramafic rocks and multiple metallogenesis[10, 11], which mainly consisted of anatexis and injection, are formed. The grade of copper and nickel in raw ore in Cu-Ni ore is 0.26% and 0.39%, respectively. Oxidation rate of copper and nickel in the ore is not high.

3. Process Mineralogy Survey

Experiment ore samples are divided four kinds: (1). dressing experiment, (2). process mineralogy experiment, (3). grindability experiment, (4). wall rock. The circuit of crushing experiment core sample is shown in Fig.3. The analysis result of composite samples for ore blending is copper 0.26%, nickel 0.39%.

3.1. Chemical Composition Analysis of Ore

The result shows the most valuable elements in ore are Cu and Ni with grade of 0.26% and 0.39%, while other metal elements are relatively low. Gangue minerals are olivine, amphibole minerals, serpentine, steatite, pyroxene minerals, chlorite, and carbonate minerals. The grade of Ni and Cu in ore is not high, and their oxidation rate is not high (Table 1, 2). The ore is primary sulfide ore.

3.2. Texture, Structure, and Mineral Constituent

Cu-Ni ore is mainly in disseminated veinlet and sulfide distribute in the form of veinlet. Sideronitic texture is the main texture of the ore and useful minerals filling the empty space between gangue mineral grains.

Hypidiomorphic and allotriomorphic pentlandite, pyrrhotite, and chalcopyrite accrete with granular structure, consisting sulfide vein. Magnetite is in vein puncture texture, but veinlet puncture texture occurs in pentlandite cleavage. Chalcopyrite occurs in gangue mineral cracks in the form of veinlet. Wallerite occurs on the surface of chalcopyrite, pyrrhotite, pentlandite, and magnetite. Steatite occurs in gangue mineral cracks or on their periphery in the form of veinlet puncture texture and rimmed texture.

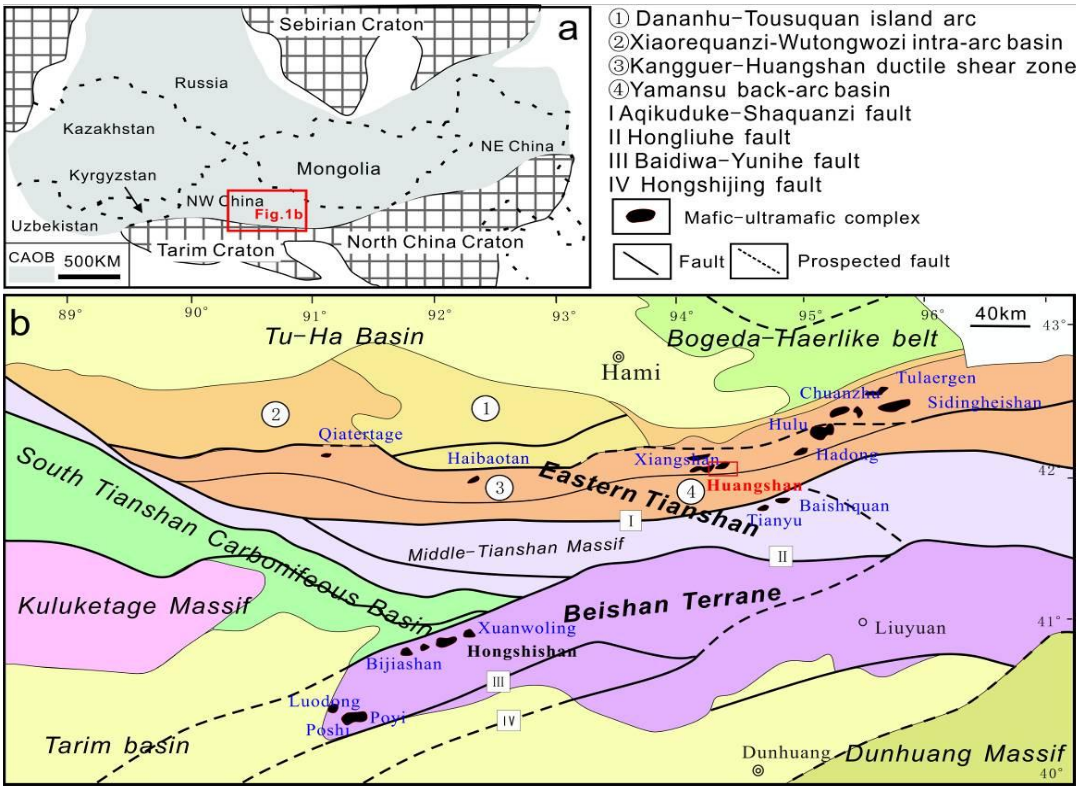

Fig.1 *Tectonic setting of mafic-ultramafic rocks and related Ni-Cu deposits in Xinjiang, NW China (Modified after Su (2014)[12] and Tang (2011)*[13] *)*

The metal minerals in Cu-Ni ore are mainly magnetite, pyrrhotite, pentlandite, chalcopyrite, wallerite, and pyrite, with chalcocite, digenite, spinel, violarite, and galena not common. Gangue minerals are mainly olivine, amphibole minerals, serpentine, steatite, pyroxene minerals, chlorite, carbonate minerals, some feldspathoid, mica group minerals, and other micro minerals (Table 4).

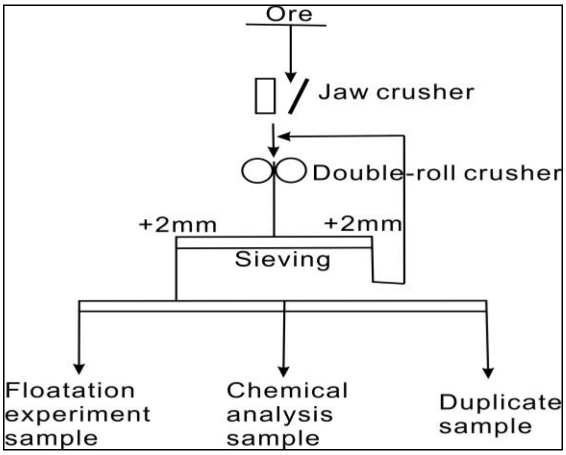

Fig.2 *Scheme illustrating the circuit of crushing experiment core sample*

Table.1 *ICP emission spectral analysis result of ore*

Composition	Co	Mo	Cu	Pb	Zn	Li	Fe	Bi	As	Mn	Ba
Amount/%	0.019	<0.01	0.27	0.03	0.11	<0.005	6.06	<0.01	0.83	0.13	<0.005
Composition	V	K	Na	Ca	Mg	Al	Sr	Ti	Ni	Sb	Sn
Amount/%	<0.01	1.42	7.70	5.54	3.51	2.59	0.011	<0.005	0.30	0.04	<0.01

Table.2 *Main chemical composition analysis result of ore*

Composition	**Ni**	**Cu**	**Pb**	**Al_2O_3**	**S**	**Fe**	**CaO**
Amount/%	0.39	0.26	0.023	3.74	2.29	10.56	3.88
Composition	Co	As	SiO_2	MgO	K_2O	Na_2O	Ag,g/t
Amount/%	0.016	0.16	39.97	29.41	0.20	0.84	6.47

Table.3 *The phase analysis result of Cu and Ni in ore*

Element in phase	**Cu in oxide**	**Cu in sulfide**	**Cu in wallerite**	**Sum of Cu /%**	**Ni in oxide**	**Ni in sulfide**	**Ni in silicate**	**sum of Ni/%**
Amount/%	0.011	0.222	0.025	0.258	0.016	0.341	0.032	0.389
Occupancy/%	4.26	86.05	9.69	100.00	4.11	87.66	8.23	100.00

Table.4 *Mineral constituent and relatively amount*

Metal minerals		**Gangue minerals**	
Mineral species	**Amount/%**	**Mineral species**	**Amount/%**
Pentlandite	1.03	Olivine	30.60
Violarite		Amphibole	15.78
Chalcopyrite	0.72	Steatite	10.69
Chalcocite		Serpentine	10.21
Digenite		Pyroxene	10.05
Vallerite	0.13	Chlorite	5.48
Pyrrhotine	3.19	Carbonate	3.20
Pyrite		Feldspar	2.10
Magnetite	4.65	Mica	1.92
Galena	0.03	Others	0.23
Sum		100.00	

3.4 Processing Property of Valuable Minerals

Pentlandite: Pentlandite is the most important Ni-bearing mineral in subhedral and euhedral form in ore, closed related with pyrrhotine and magnetite. Most of them accrete together. Pentlandite's particle size is coarse in the value of 0.020~0.800mm. Some pentlandite contain Ni, Fe, S, and minor Co. Some pentlandite doesn't contain Co.

Chalcopyrite: Chalcopyrite is the main Cu-bearing mineral in subhedral and xenomorphic form. Pentlandite has ordinary relationship with it. Magnetite and vallerite don't have close relationship with it. Chalcopyrite's particle size is coarse in the value of 0.020~0.800mm.

Pyrrhotine: Pyrrhotine is the important metal sulfide in subhedral and xenomorphic form. Pentlandite and chalcopyrite have close relationship with it. Pyrrhotine's particle size is coarse in the value of 0.020~1.170mm. Some of it contains Fe, S, and minor Ni. Some of it doesn't contain Ni.

Vallerite: Vallerite is one of Cu-bearing minerals in xenomorphic form. Only some of it occurs around the edge of chalcopyrite. Vallerite's particle size is fine in the value of 0.010~0.020mm. The amount of Cu in Vallerite is 19.38%.

Magnetite: Magnetite is one of the most important metal minerals in xenomorphic form in ore. Magnetite's particle size is usually 0.010~0.043mm.

Steatite: Steatite is gangue mineral with excellent natural floatability in ore. Its amount in sample is high. If don't handle it, the effect of flotation will be badly influenced. Steatite's particle size is coarse, generally >0.043mm.

Serpentine: Serpentine is gangue minerals with excellent natural floatability in ore. Steatite's particle size is coarse generally >0.043mm.

3.5 Grain size of dominant metal minerals in ore

Disseminated grain size of minerals is important to design grinding process. Therefore, the disseminated grain size of pentlandite, copper mineral aggregates, pyrrhotine, and sulfide aggregates is systematically examined with line section under microscope.

3.6 The occurrence state of Ni, Cu, S and Fe in ore at the beneficiation process

Ni: The grade of Ni in ore is 0.39%. Ni in ore is mainly in the form of sulphide hosted in pentlandite. In the flotation operation, most of pentlandite will come into the nickel concentrate with a low loss of fine-grained pentlandite in the tailings.

Cu: The grade of Cu in ore is 0.26%.Cu in ore is mainly in the form of chalcopyrite and the remaining in the form of valleriite, chalcocite, digenite. In the flotation operation, most of chalcopyrite, chalcocite, digenite will come into the copper concentrate with a low loss of fine-grained chalcopyrite, chalcocite, digenite in the tailings. Valleriite exist in symbiosis and other sulphide will also come into copper concentrate with a high loss of valleriite in the tailings.

Table 5 *The main mineral size and composition*

Size(mm)	**Copper minerals %**		**Nickel minerals %**		**Pyrrhotite %**		**The total sulfides %**	
	Content	**In total**	**Content**	**In total**	**Content**	**In total**	**Content**	**In total**
+2.000					2.22	2.22	1.70	1.70
-1.651+2.000					0.96	3.18	0.74	2.44

-1.168+1.651	3.33	3.33			5.20	8.38	5.71	8.15
-0.833+1.168	4.73	8.06	7.71	7.71	4.22	12.60	6.08	14.23
-0.589+0.833	11.77	19.83	5.48	13.19	7.50	20.10	10.36	24.59
-0.417+0.589	5.95	25.78	7.75	20.94	13.26	33.36	8.55	33.14
-0.295+0.417	9.26	35.04	12.34	33.28	12.77	46.13	13.69	46.83
-0.208+0.295	5.95	40.99	7.75	41.03	10.48	56.61	9.88	56.71
-0.147+0.208	9.66	50.65	15.73	56.76	9.83	66.44	10.56	67.27
-0.104+0.147	7.72	58.37	10.64	67.40	6.49	72.93	6.45	73.72
-0.074+0.104	10.10	68.47	11.32	78.72	9.34	82.27	8.18	81.90
-0.043+0.074	9.55	78.02	10.59	89.31	7.25	89.52	7.01	88.91
-0.020+0.043	11.77	89.79	7.52	96.83	6.51	96.03	6.66	95.57
-0.015+0.020	4.26	94.05	1.82	98.65	1.89	97.92	1.97	97.54
-0.010+0.015	3.78	97.83	1.16	99.81	1.39	99.31	1.62	99.16
-0.010	2.16	100.00	0.19	100.00	0.69	100.00	0.83	100.00

S: The grade of S in ore is 0.26%. The hosted mineral of Cu is mainly pyrrhotite with partly pentlandite and chalcopyrite,and other sulfides in small amounts. In the flotation operation, most of pyrrhotite will come into the tailings with a small amount of it in the copper and nickel concentrate;Most of pentlandite and chalcopyrite will come into copper and nickel concentrate respectively.

4. Discussion

The grade of Ni and Cu in copper-nickel mine is 0.39% and 0.26%, respectively. The mine should be the primary sulfide ore for Ni and Cu because their low oxidation rate in ore. The main metallic minerals are pyrrhotite, followed by chalcopyrite, pentlandite, magnetite. The main gangue minerals are talc, serpentine, carbonate minerals, followed by chlorite, mica minerals.

The ore is copper-nickel mine with high magnesia content of up to 29.41% and low-grade. The main gangue minerals are talc, serpentine based, which brings great influence to the beneficiation[14]. For these characteristics of ore, two exploration tests are carried out:1.copper-nickel mixed selection - copper-nickel separation test; 2 pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test.According to the above mentioned, the beneficiation procedure of copper-nickel ore is shown in figure 3.

Fe: Nearly 32% of Fe is in the form of magnetite and nearly 45% of Fe combined with sulfur is in the form of pyrrhotite and pyrite with a small amount of it in chalcopyrite and gangue minerals. Since it is difficult for fine-grained magnetite in ore to recycle, it will come into the tailings in beneficiation processes.

4.1 Cu-Ni Mixed Floating-Mixture Concentrate Separation Test

The nickel concentrate has high copper content of 1.66%, high magnesia content of 9.81% (Table 6). Since the former copper-nickel mixed election without prior removal of talc, making some easy to float talc, serpentine into rough concentrate, is likely to cause the mineral rate, low selection efficiency, large amount of reagent and other phenomena, serious deterioration copper-nickel flotation environment[15]. Copper-nickel featured partially buoyant job talc, serpentine is not easy to CMC suppressed, resulting in high MgO content of nickel concentrate after copper and nickel separation[16]. To reduce talc, serpentine influence on the sorting process, the use of its zooplankton and good, if it is to advance sorting out, it is possible to reduce the impact of these minerals to the process. Therefore it has been pre-flotation talc - copper-nickel mixed floating - concentrate mixture separation process tests[17].

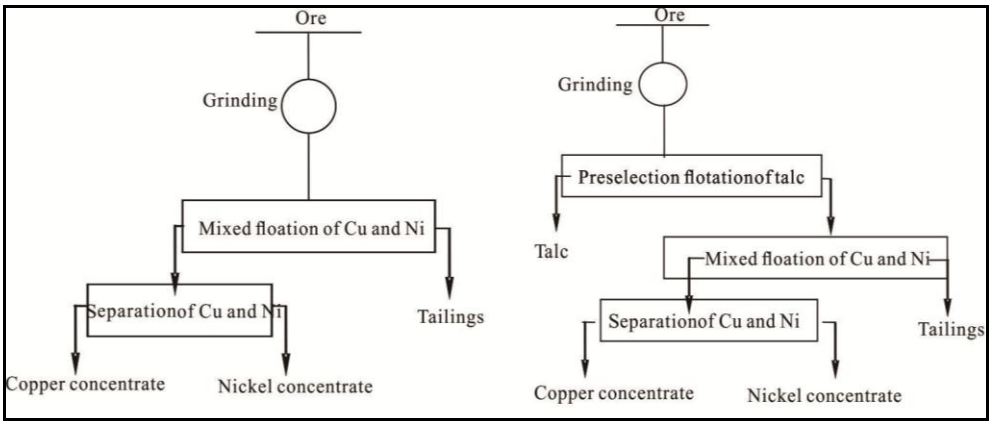

***Fig.** 3 Cu-Ni mixed selection (a) and pre-removal talc Cu-Ni mixed selection-separation test (b).*

Table 6 *The results of Cu-Ni floating - mixture concentrate separation test*

Products name	Productivity %	Grade %			Recovery %	
		Cu	Ni	MgO	Cu	Ni
Copper	0.25	23.95	1.51	9.81	23.44	0.98
Middlings1	0.26	15.38	2.28		15.56	1.53
Middlings2	0.29	6.96	3.82		7.95	2.90
Nickel	1.01	1.66	6.46		6.50	16.80
Middlings3	5.10	0.38	2.1		7.53	27.63
Middlings4	17.48	0.19	0.55		12.90	24.80
Tailings	75.61	0.089	0.13		26.13	25.35
Raw ore	100	0.26	0.39		100	100

Table 7 *The results of pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test*

Product name	Productivity %	Grade %			Recovery %	
		Cu	Ni	MgO	Cu	Ni
Talc	5.74	0.097	0.093	5.22	2.18	1.39
Middlings1	3.70	0.25	0.18		3.62	1.73
Copper	0.26	24.52	1.45		24.98	0.98
Middlings2	0.29	16.84	4.96		18.82	3.68
Middlings3	0.37	3.31	5.38		4.79	5.17
Nickel	1.01	1.51	9.67		5.96	25.32
Middlings4	7.81	0.35	1.59		10.69	32.23
Middlings5	4.88	0.18	0.46		3.44	5.83
Tailings	75.95	0.086	0.12		25.54	23.67
Raw ore	100.0	0.26	0.39		100.0	100.0

Since the talc is not prior removed previously before the mixed selection of Cu-Ni, which makes buoyant talc and serpentine into rough concentrate easily, and results in high mineral rate, low selection efficiency, large consumption of medicine and serious deterioration in Cu-Ni flotation environment. Buoyant talc and serpentine is not easily suppressed by CMC in Cu - Ni selection operations, which results in high MgO content of nickel concentrate after Cu-Ni separation. In order to reduce the influence of talc and serpentine on the sorting process, it is possible to reduce the impact of the process if sorting out them in advance using of their good floatability. Next is the pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test.

4.2 Pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test

According to the test results, the test will remove most of talc due to the high magnesium content of ore, and greatly improve Cu-Ni flotation environment with magnesia content of nickel concentrate reduced to 5.22%. However, the interoperability of copper and nickel concentrate is still high, which indicates that it is not ideal to use lime inhibit nickel minerals[18].

By the comparison of these two tests: the former can greatly reduce the amount of medicine, Improve Cu - Ni flotation environment, make field production more stable and easier to operate, and get better indicator.

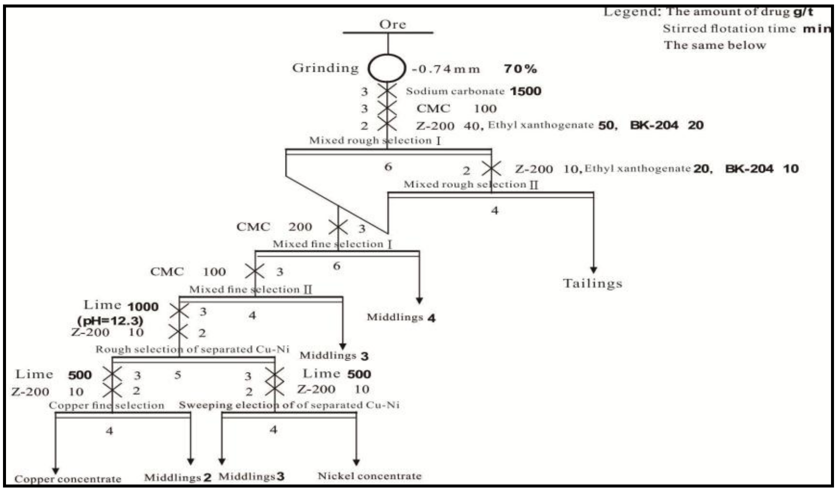

Fig. 4 *Process of floating-mixture concentrate separation test*

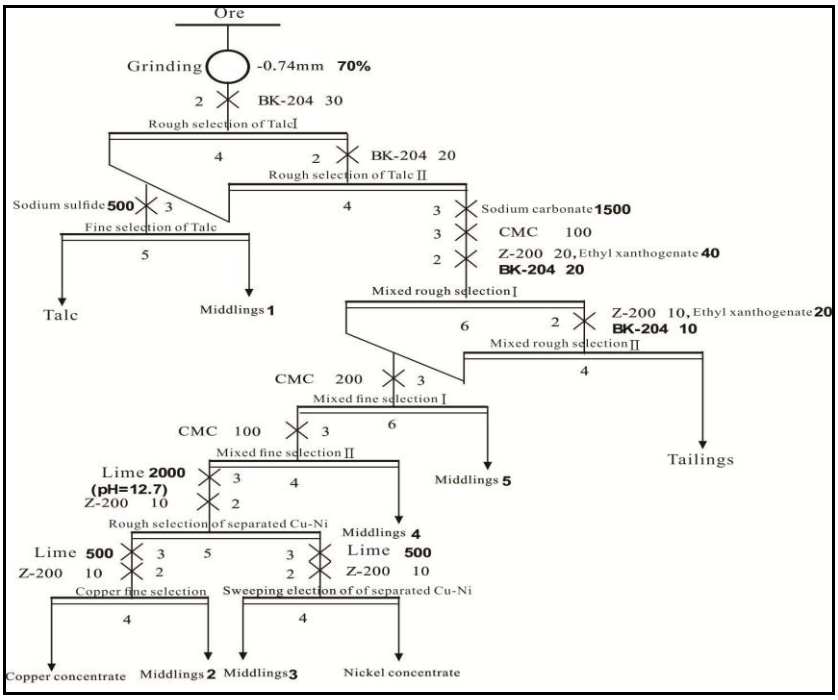

Fig. 5 *Pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test*

Table 8 *Closed-circuit test results of Cu-Ni mine*

Product	Productivity %	Grade %			Recovery %		
		Cu	Ni	MgO	Cu	Ni	MgO
Talc	6.84	0.11	0.089	38.65	2.84	1.57	9.00
Copper	0.85	20.58	0.89	1.89	66.38	1.96	0.05
Nickel	2.73	0.95	10.46	5.61	9.80	73.80	0.52
Mixed Cu-Ni	3.58	5.62	8.18	4.72	76.18	75.76	0.57
Tailings	89.58	0.062	0.098	29.65	20.98	22.67	90.42
Raw ore	100.0	0.26	0.39	29.37	100.0	100.0	100.0

5. Conclusion

(1) The grade of Ni and Cu in ore is not high, corresponding to 0.39% and 0.26% respectively and the same with their oxidation rate. Therefore, the mine should be the primary sulfide ore for Ni and Cu.

(2) The mineral composition of the ore is relatively complex with Ni, Cu, S and Fe in the form of independent minerals. The independent minerals of Ni are mainly pentlandite with violarite in very small amounts. The independent minerals of Cu are mainly chalcopyrite with valleriite in some amount, chalcocite and digenite in very small amounts. The independent minerals of S are mainly pyrrhotite with pyrite in very small amounts. The minerals of Fe are mainly magnetite with hematite and limonite in very small amounts. The gangue minerals are olivine and amphibole minerals, followed by serpentine, talc, pyroxene, chlorite and carbonate minerals, but also a small amount of feldspar, mica minerals and other minerals.

(3) The main configuration of ore contains disseminated-,vein-, banded-structure, etc. Ore structure is complex that contains grain-, euhedral-,subhedral-,containing-,interstitial-, vein-, stock work-, co-edge -, dissolution-, rimmed -texture, etc.

(4) It is difficult to dissociate pentlandite and chalcopyrite effectively in mine grinding because of their close relationship even though their grain size is coarse, so it is necessary for rough concentrate of whole sulfur flotation to regrinding. It is difficult to recycle magnetite because of its fine stock work structure.

(5) According to these characteristics, We carry on two tests including Cu-Ni mixed floating - mixture concentrate separation test and pre-removal talc - Cu-Ni mixed selection - Cu-Ni separation test,and we conclude that the former can achieve satisfactory indicators.

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References

[1] Su B. Mafic-ultramafic Intrusions in Beishan and Eastern Tianshan at Southern CAOB: Petrogenesis, Mineralization and Tectonic Implication[M]. Springer Berlin Heidelberg, 2014.

[2] Han C, Xiao W, Zhao G, et al. In-situ U–Pb, Hf and Re–Os isotopic analyses of the Xiangshan Ni–Cu–Co deposit in Eastern Tianshan (Xinjiang), Central Asia Orogenic Belt: Constraints on the timing and genesis of the mineralization[J]. Lithos. 2010, 120(3-4): 547-562.

[3] Xiao W J, Windley B F, Allen M B, et al. Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage[J]. Gondwana Research. 2013, 23(4SI): 1316-1341.

[4] Xiao W, Zhang L, Qin K, et al. Paleozoic accretionary and collisional tectonics of the Eastern Tianshan (China): implications for the continental growth of central Asia[J]. American Journal of Science. 2004, 304(4): 370-395.

[5] Jingwen M, Jianmin Y, Wenjun Q, et al. Re-Os Age of Cu-Ni Ores from the Huangshandong Cu-Ni Sulfide Deposit in the East Tianshan Mountains and Its Implication for Geodynamic Processes[J]. Acta Geologica Sinica-English Edition. 2003, 77(2): 220-226.

[6] Mao J W, Pirajno F, Zhang Z H, et al. A review of the Cu–Ni sulphide deposits in the Chinese Tianshan and Altay orogens (Xinjiang Autonomous Region, NW China): principal characteristics and ore-forming processes[J]. Journal of Asian Earth Sciences. 2008, 32(2): 184-203.

[7] Deng Y F, Song X Y, Jie W, et al. Petrogenesis of the Huangshandong Ni-Cu sulfide-bearing mafic-ultramafic intrusion, northern Tianshan, Xinjiang: Evidence from major and trace elements and Sr-Nd isotope[J]. Acta Geologica Sinica. 2011, 85(9): 1435-1451.

[8] Sun T, Qian Z, Deng Y, et al. PGE and Isotope (Hf-Sr-Nd-Pb) Constraints on the Origin of the Huangshandong Magmatic Ni-Cu Sulfide Deposit in the Central Asian Orogenic Belt, Northwestern China[J]. Economic Geology. 2013, 108(8): 1849-1864.

[9] Xia M, Jiang C, Li C, et al. Characteristics of a Newly Discovered Ni-Cu Sulfide Deposit Hosted in the Poyi Ultramafic Intrusion, Tarim Craton, NW China[J]. Economic Geology. 2013, 108(8): 1865-1878.

[10] Zhou M, Michael Lesher C, Yang Z, et al. Geochemistry and petrogenesis of 270 Ma Ni–Cu–(PGE) sulfide-bearing mafic intrusions in the Huangshan district, Eastern Xinjiang, Northwest China: implications for the tectonic evolution of the Central Asian orogenic belt[J]. Chemical Geology. 2004, 209(3): 233-257.

[11] Gao J, Zhou M, Lightfoot P C, et al. Sulfide Saturation and Magma Emplacement in the Formation of the Permian Huangshandong Ni-Cu Sulfide Deposit, Xinjiang, Northwestern China[J]. Economic Geology. 2013, 108(8): 1833-1848.

[12] Su B, Qin K, Sakyi P A, et al. Geochronologic-petrochemical studies of the Hongshishan mafic–ultramafic intrusion, Beishan area, Xinjiang (NW China): petrogenesis and tectonic implications[J]. International Geology Review. 2012, 54(3): 270-289.

[13] Tang D, Qin K, Li C, et al. Zircon dating, Hf–Sr–Nd–Os isotopes and PGE geochemistry of the Tianyu sulfide-bearing mafic–ultramafic intrusion in the Central Asian Orogenic Belt, NW China[J]. Lithos. 2011, 126(1-2): 84-98.

[14] Lu Z, Cai M. Disposal Methods on Solid Wastes from Mines in Transition from Open-Pit to Underground Mining[J]. Procedia Environmental Sciences. 2012, 16: 715-721.

[15] Gaskova O L, Bukaty M B, Shironosova G P, et al. Thermodynamic model for sorption of bivalent heavy metals on calcite in natural-technogenic environments[J]. Russian Geology and Geophysics. 2009, 50(2): 87-95.

[16] Dobretsov N L, Pokhilenko N P. Mineral resources and development in the Russian Arctic[J]. Russian Geology and Geophysics. 2010, 51(1): 98-111.

[17] Had I Jordanov S, Maleti M, Dimitrov A, et al. Waste waters from copper ores mining/flotation in‘Bubim’ mine: characterization and remediation[J]. Desalination. 2007, 213(1–3): 65-71.

[18] Gregurek D, Reimann C, Stumpfl E F. Trace elements and precious metals in snow samples from the immediate vicinity of nickel processing plants, Kola Peninsula, northwest Russia[J]. Environmental Pollution. 1998, 102(2–3): 221-232.