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The effect of grinding circuit efficiency on the grade and recovery of copper and molybdenum concentrates

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ABSTRACT

The efficiency of grinding and flotation process in copper-molybdenum processing circuit, largely affected by performance of thickeners and hydrocyclones devices. The goal of this paper is to investigate the effect of the rate-limiting factors on the performance of these devices and consequently on grinding and separation efficiency of the molybdenum processing circuit. So, a full process mineralogical study have been carried out on outputs of thickeners and hydrocyclone of the molybdenite flotation circuit. According to the results, coarse-grained fractions (>50 μm) of the planar molybdenite will not necessarily be recovered by thickener and hydrocyclones. This is especially true for hydrocyclones when the inlet-load rate is high, i.e., the erroneous discharge of planar molybdenite particles from the overflow of hydrocyclone, as well as their floatability in the thickener overflow, can be attributed to the effect of particle shape and size. This issue harms the grade and recovery of flotation due to the increase in the amount of circulating load (regrinding) and consequently the generation of fine particles (<10 μm) in the hydrocyclone-milling circuit. On the other hand, the almost spherical particles of copper minerals, as well as the nonplanar molybdenite fine-grained particles, are easily removed from the hydrocyclone underflow or settled in thickeners. The introduction of copper mineral particles into molybdenum concentrate and vice versa has reduced the quality of the produced concentrate and undesirable flotation performance.

Introduction

Almost half of the world's molybdenum reserves are in the form of copper – molybdenum porphyry ores (USGS, 2020). Due to the differences between the surface properties of molybdenite and other sulfides, molybdenum can be obtained from these ores as copper by-products (Castro, Lopez-Valdivieso, and Laskowski 2016). Processing of Cu – Mo ores consists of two steps: a bulk flotation where molybdenite is recovered with Cu sulfides, and a subsequent selective flotation step where molybdenite is separated from depressed copper sulfides (Nikonow and Rammlmair 2022). Cu-Mo concentrate (product of copper – molybdenum processing plant) is introduced into Cu-Mo concentrate thickeners to increase the solid percentage and reduce the chemical content of pulp used in copper – molybdenum flotation. The underflow of Cu-Mo concentrate thickeners is the feed to the molybdenum processing plant (Castro and Laskowski 2015). In Cu-Mo concentrate processing, the molybdenum processing circuit input load enters the middle thickener after undergoing the

separation process in the rougher and cleaner flotation cells (primary and secondary). The underflow of the middle thickener for the purpose of comminution is directed to the primary mill (ball mill), and its overflow is used as process water. The milling product is transferred to the cleaner flotation cells, and then the subsequent concentrate is loaded into the closed-circuit mill (ball mill-hydrocyclone) to increase the degree of liberation of the molybdenite mineral. The hydrocyclone overflow, after several flotation steps (usually four steps), is finally transferred to the dewatering thickener as the final concentrate product (molybdenum) (Abdollahi et al. 2020). It should be noted that molybdenum plant tailings are the final copper concentrate that enters the final copper thickener like the final molybdenum concentrate (Bahrami et al. 2020).

In the molybdenite processing circuit, hydrocyclones and thickeners are utilized for particle classification, settling, and increasing the solid percentage of slurry. Particle size distribution (PSD) and shape are key parameters affecting the efficiency of these classifications and dewatering instruments (Tang et al. 2019). In addition, the particle shape is an important industrial parameter for predicting behavior in downstream processes (Ahmed 2010). Besides settling behavior and particle classification, the shape parameter affects recovery, fluid flow, floatability, agglomeration, fluidity and structural form of materials (Dehghani et al. 2019). Irregularly shaped particles due to nonsymmetrical and non-geometric shapes settle at a slower rate than spherical particles (Tang et al. 2019). Decreasing the surface of the sphere and increasing the predicted surface, in turn, increases the tension, so they tend to orient, and take different routes in a preferred path during their fall. This optimal orientation is generally unpredictable and depends on the position of their center (of particles) of gravity relative to the center. Roughness also increases the surface area of drag forces (Mohammed and Halagy 2013).

Although weak van der Waals bonds hold successive layers of sulfur atoms together in the molybdenite mineral structure, however, molybdenum and sulfur atoms are bonded together in layers with strong covalent bonds (Castro and Laskowski 2015). The bond between S-S and Mo-Mo is van der Waals and S-Mo-S is covalent (Zanin et al. 2009). Due to that, molybdenite has anisotropic properties, which is the main reason for its different behavior in various faces (Kim, Huang, and Lieber 1991). Among other things, the anisotropic property causes the preferential orientation of the molybdenite mineral during comminution; and as the particle size decreases, this orientation increases. Thus, during comminution, molybdenite is broken into two different surfaces. The surfaces are created by breaking S-S bonds (nonpolar surfaces), and the surfaces result from the rupture of strong Mo-S bonds. Since the van der Waals bond is weaker than the covalent bond, the probability of failure is greater than the edges. These properties affected on flotation of molybdenite; also other minerals as ilmenite (Cai et al. 2020) and coal (Cheng et al. 2020) have individual behavior in the flotation.

Due to the multiplicity of classification and dewatering apparatus including hydrocyclones and thickeners in the molybdenite processing circuit, the study of operation mechanism of these devices is imperative. Numerous studies have been conducted on the efficiency of classification and dewatering process on downstream processes such as grinding and flotation. For example, Albuquerque, Valine, and Wheeler (2011) investigated the role of the hydrocyclone in the grinding circuit, and the possibility of replacing it with other equipment with similar function (including sieve). Bahrami et al. (2020) conducted a similar study on the effect of hydrocyclone on the grinding circuit of molybdenite. Abdollahi et al. (2020) investigated the efficiency of flotation circuit affected by molybdenite grinding circuit. Saramak and Saramak, (2022) conducted similar research about grinding – degree of liberation and their effect on downstream process. Based on these studies, the proper efficiency and effectiveness of the aforementioned instruments will have an actual impact on the final separation performance of the processing circuit. For example, the proper hydrocyclone operation, in addition to the reduction in milling energy consumption, affects other downstream processes such as flotation, dewatering, and filtration due to changes in product particle size. Also, several studies such as study done by Kashiwaya et al. (2012), Mohammed and Halagy (2013), Jankovic, Valery, and Sonmez (2013), Tang et al. (2019), Garmsiri and Unesi (2018), Dehghani et al. (2019) and Wang et al. (2022), have been conducted on the effect of particle shape on the performance of the

mentioned instruments and for various minerals, mainly focusing on aspects of process simulation and modeling. In the present study, first an attempt has been made to investigate the effect of particle size and shape parameters of minerals (copper minerals and molybdenite) on the performance of classification and settling processes, afterward the effect of the efficiency of these devices (affected by the shape and size of copper and molybdenite minerals) on the final separation performance of the molybdenum processing circuit has been investigated. The present study was done on the industrial scale in Sungun Copper – Molybdenum Processing Complex (Northwestern Iran). The purpose of this study is to improve the efficiency of molybdenum flotation circuit by investigating and optimizing the separation and dewatering systems in the circuit. In this way, is tried to optimize the molybdenum processing circuit by utilizing process mineralogy. To achieve this goal, a full detailed process mineralogical approach were conducted as follows:

- Rate-limiting factors studied,
- Analytical techniques and methods used for mineral characterization and chemical analysis include PSD, optical image analysis (OIA), scanning electron microscopy (SEM) and chemical analysis, and,
- Operation parameters, e.g., pulp flow, classification processes of hydrocyclone and settling in molybdenum processing plant thickeners investigated.

Materials and methods

Molybdenite processing circuit

The present study was conducted to investigate the performance of classification and dewatering devices including hydrocyclones and thickeners of molybdenum flotation circuit in the copper-molybdenum processing complex of Sungun. Sungun Copper Complex with geographical coordinates of 46° 43' E and 38° 42' N is located in northwestern Iran. In the molybdenum processing plant of this complex (flowsheet is presented in Figure 1), four thickeners are utilized to settle and increase the pulp solid concentration, and one hydrocyclone is used to classify and increase the pulp solid percentage. Table 1 lists the specifications for this apparatus.

Process mineralogy studies

In this research, process mineralogy has been studied for the classification and dewatering processes of the molybdenum processing circuit. To perform process mineralogical studies, the circuit shown in Figure 1 was sampled at steady-state conditions and from multiple branches of the circuit. Flow points are marked with the red line in Figure 1. Samples were taken via a sampling spoon; to investigate changes in the mineralogical properties of products (such as grade, particle size, etc.); three samples within a 1-hour interval were taken from each sampling location at different operational shifts. The total sample volume for each location was about 1.11 liter. It should be noted that the sampling period was approximately 14 days. Process mineralogical studies have been conducted via PSD analysis, chemical composition, and microscopic studies (optical and electron microscopy). In addition, to optimize the performance of the mentioned processes, the results of these studies have been combined with the operating conditions of the existing circuit and then analyzed.

For all samples introduced and collected from the circuit shown in Figure 1, including Cu-Mo thickener underflow (input load to a molybdenum processing plant), input load to copper concentrate thickener, inlet load-overflow-middle thickener underflow, inlet load-overflow-hydrocyclone under-flow, and inlet load to molybdenum concentrate thickener, PSD analysis has been carried out. PSD analysis is conducted via laser particle size analyzer (SLS: Mastersizer 2000/Malvern Panalytical technology). To this end, after filtering and drying, 30 g of the sample was prepared using a riffle sample splitter to check the size distribution.
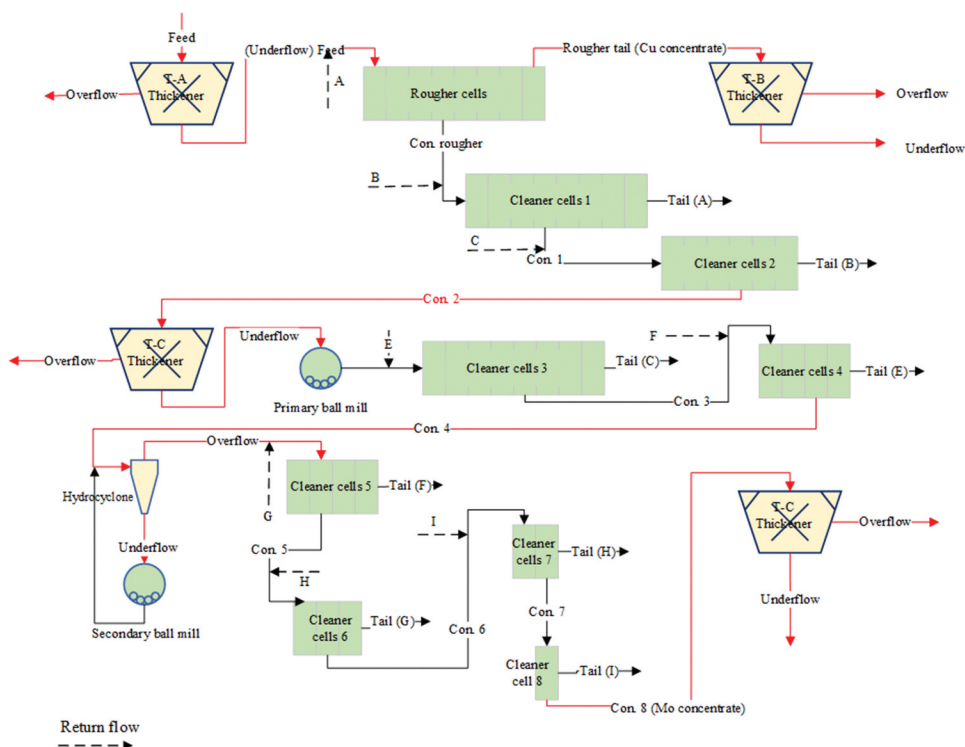
Figure 1. Molybdenum processing circuit, Sungun Copper – Molybdenum processing complex.

Table 1. Specifications and operational parameters of thickener and hydrocyclones of molybdenum processing circuit (copper-molybdenum processing complex of Sungun).

			Thickeners			
Code	Description code	Diameter (m)	High (m)	Feed solid wt.%	Feed tonnage (m³/h)	Density of solid (ton/m³)	Settling mechanism
T-A	Initial thickener (Mo-Cu)	24.00	6.00	28.60	81.60	4.20	Free settling
T-B	Cu con. Thickener	12.00	3.00	40.09	16.00	4.70	Flocculants (Polyacrylamide)
T-C	Middle thickener	12.00	3.21	10.82	35.10	4.35	Free settling
T-D	Mo con. thickener	12.00	3.21	6.36	16.00	4.70	Flocculants (Polyacrylamide)

	Hydrocyclone			
Diameter (mm)	Number of clusters	Cyclone in each cluster	Cut size (µm)	Feed solid wt.%
150.00	2	3	38.00	11.72

To investigate the behavior of different minerals in the classifiers and dewatering instruments of the molybdenite flotation circuit, polished sections were prepared, and optical and electronic microscopy studies were performed. Based on size analysis, most of the samples contain particles smaller than 25 µm. A cyclosizer was utilized to classify the particles. However, due to the planar shape of the molybdenite particles, as well as its adhesion and grease-like properties, the mineral particles adhere to the inner walls of the instrument. Therefore, a highly flawed classification was encountered, and it was technically impossible. Thus, due to the difficulty of classifying the samples into different size fractions, the representative sample for polished sections is taken from the raw sample (without

Table 2. Solid pulp percentage and titration analysis of inlet and outlet flows to hydrocyclones and molybdenum processing circuit thickeners.

Flow	Solid wt.%	Grade %		
		Mo	Cu	Fe
Underflow thickener Mo-Cu	50.00	0.47	25.48	31.74
Feed thickener con. Cu	40.09	0.08	27.16	32.03
Feed middle thickener	10.82	16.30	17.03	17.50
Overflow middle thickener	0.04	20.52	5.00	9.75
Underflow middle thickener	42.00	15.20	18.02	17.57
Feed hydrocyclone	11.72	39.34	4.94	10.34
Overflow hydrocyclone	10.68	38.45	4.78	10.76
Underflow hydrocyclone	14.81	39.99	3.96	10.34
Feed thickener con. Mo	6.36	48.70	1.46	5.22
Underflow thickener con. Mo	65.00	48.70	1.46	5.22

classification). Microscopic studies were carried out using a polarizing optical microscope (Leitz Model SM-LUX-POL) equipped with a digital imaging camera, and scanning electron microscopy (SEM, FEI Model QUANTA 450).

To determine the operating conditions of the circuit, the pulp solid percentages of all branches of the studied stream were determined. The results are shown in Table 2. After the determination of solid mass and weight, X-ray fluorescence (×RF) analysis was performed to measure the Mo content. Atomic absorption spectroscopy (AAS) was used to measure Cu and Fe content. Table 2 shows the results of Mo, Cu, and Fe grade analysis for each branch of the studied stream.

Results and discussion

The effect of particle size parameter on the efficiency of dewatering-classification devices

A) Primary thickeners or copper-molybdenum concentrate (code T-A): The input load to the thickener T-A (copper-molybdenum concentrate) contains all kinds of chemicals used in the copper processing plant. This thickener is more important from the dewatering efficiency and production of underflow with a higher solid percentage standpoint; therefore, the soluble chemicals in the input load of this thickener will affect the molybdenite flotation performance and copper depression. For example, the presence of sodium sulfate at the input load to the T-A thickener, which is used to reduce Eh in the copper flotation circuit, will affect the particle flotation mechanism in the molybdenite flotation process.

Investigation of changes in PSD at the inlet load and outlet flows of classifiers and dewatering equipment can provide useful information regarding the particle classification and settling process, and how that device operates. Figure 2 shows a diagram of the PSD of copper-molybdenum thickeners or the inlet load to the molybdenum plant. According to this diagram, more than 90% of the particles entering the molybdenum flotation circuit are less than 50 μm. About 50% of *T*-A thickener underflow particles are less than 10 μm, which are in the range of fine-grained particles.

B) Copper and molybdenum concentrate thickeners (code T-B and T-D): According to the flowsheet presented in Figure 1, by conducting flotation operation on the input load to the circuit (T-A thickener underflow), the resulted tailings from the flotation circuit will be transferred to tailings thickener (T-B copper concentrate) and the concentrate product is directed to the molybdenum concentrate thickener (T-D). In copper and molybdenum concentrate thickeners, the underflow of thickeners after filtering are considered as final products. The overflow of these thickeners is used as return water in the molybdenum flotation circuit. The overflow of these thickeners contains the chemicals used in the molybdenum flotation circuit, including diesel (collector for molybdenite), sodium hydrosulfide, sodium cyanide, and ammonium sulfide (copper mineral depressant), and EXfome 636 (frother); which is utilized as a return in the circuit. Reuse of the mentioned chemicals
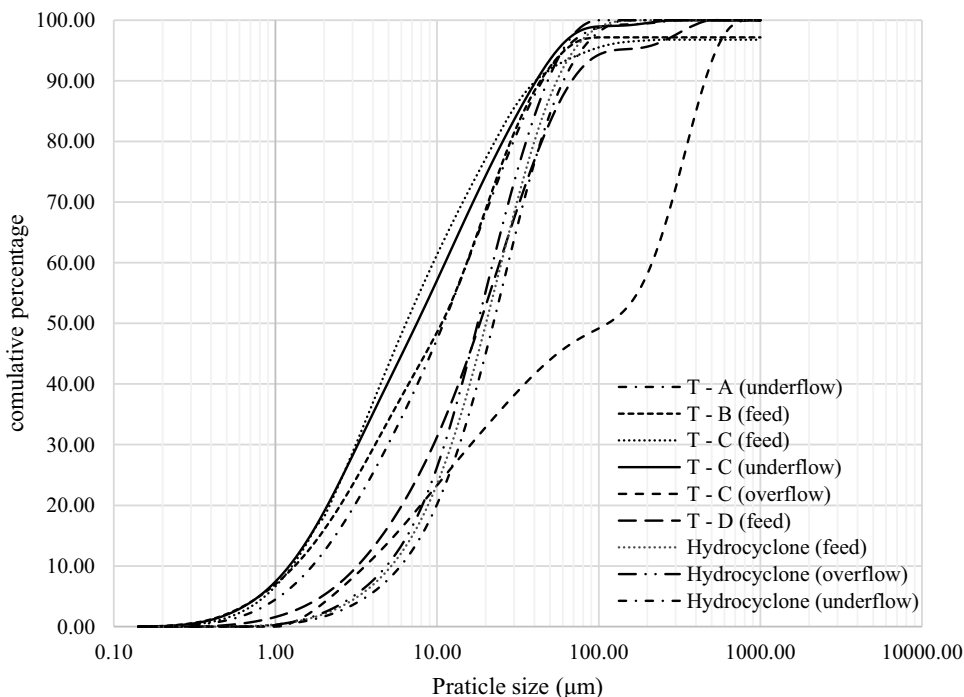
Figure 2. PSD graphs of inlet load, overflow, and underflow of thickener and hydrocyclone, molybdenum-processing plant.

Table 3. PSD of input and output load to thickeners and hydrocyclone of molybdenum flotation circuit.

Code	Flow	d_{10} (µm)	d_{50} (µm)	d_{90} (µm)
T – A	Underflow thickener Mo-Cu	1.692	10.975	44.824
T – B	Feed thickener con. Cu	1.317	10.675	42.508
T – C	Feed middle thickener	1.269	6.188	36.147
T – C (O)	Overflow middle thickener	3.592	113.827	454.061
T – C (U)	Under flow middle thickener	1.367	8.406	46.016
	Feed hydrocyclone	2.884	17.846	53.177
	Overflow hydrocyclone	2.223	16.389	52.566
	Underflow hydrocyclone	3.102	19.819	54.397
T – D	Feed thickener con. Mo	2.87	16.409	60.955

in the overflow of concentrate thickeners will reduce the consumption of chemicals and as a result, it will be economical, as well as prevent their entry into the environment and its subsequent pollution.

The PSD diagram of the input load to the *T*-B and *T*-D thickeners is shown in Figure 2. Table 3 shows the values of d_{90}, d_{50}, and d_{10} of the PSD diagrams. The overflow solid percentages of *T*-A, T-B, and T-D thickeners are very low and less than 0.001% and contain only chemicals used in copper and molybdenum flotation circuits. Therefore, it can be argued that the PSD diagram of input load to these thickeners is similar to their underflow. As can be seen in Figure 2, the underflow of thickener T-B has the same PSD diagram as the T-A thickener underflow. It is obvious that due to the lack of comminution, during the rougher flotation process, the separation between copper and molybdenum sulfide minerals has taken place, and therefore no significant difference has been made in the PSD diagram. Only due to the small difference in d_{90} between these two diagrams, it can be inferred that the frequency of coarse particles in the underflow of thickener T-A is higher than that of thickener T-B. According to Table 2, the molybdenum grade in underflows of thickener T-A and T-B are 0.47% and 0.08%, respectively. Therefore, coarse particles are more associated with molybdenite minerals. Comparing the thickener T-D PSD diagram with the other two cases (Figure 2 and Table 3), it can be

seen that the particles in the thickener underflow of molybdenum concentrate have a larger distribution than the underflow of T-A and T-B thickeners; which confirms the claim that molybdenite particles are coarser than copper sulfide minerals. The presence of S-Mo-S covalent bond in the structure of molybdenite causes the failure of this mineral in the direction of its edges. Therefore, despite performing two re-grinding steps during molybdenum processing, the molybdenite mineral particles still have a coarse-grained distribution. Due to preferential cleavages of weak S-S and Mo-Mo bonds during the comminution process, planar fragments of larger particles are generated. In general, it can be stated that in the case of molybdenite mineral particles, their shape parameter had a greater effect on particle settling than the particle size parameter. As in the middle (T-C) and final molybdenum (T-D) thickeners, the problems related to molybdenite particle settling are more pronounced than in copper-molybdenum thickeners (T-A) and especially the final copper thickener (T-B).

(A) **Molybdenum plant middle thickener (code T-C):** The diagrams in Figure 2 and Table 3 show the PSD results of the inlet load, underflow, and overflow of the middle thickener (T-C) of the molybdenum plant. PSD diagram of the middle thickener overflow has a coarser size distribution than feed and underflow. Despite the very low percentage of solid overflow (0.04%) and its very low solid discharge (less than 0.001%), it can be argued that in some cases the lack of planar molybdenite coarse-grained particles settling (which has a surface with oily properties), is the reason that the PSD diagram of overflow is more coarse sized than feed and underflows. According to the graphs shown in Fig.ure 2, in fine size fractions, feed and underflow of middle thickener have almost the same PSD. While in the size fractions of 7–15 µm and 15–28 µm, thickener underflow has a finer PSD than feeds. In particles larger than 30 µm, this trend can be seen with less variance.

(B) **Hydrocyclone of molybdenum flotation circuit:** The PSD diagrams shown in Fig.ure 2 are related to the inlet load, underflow, and overflow of hydrocyclone in the molybdenum processing circuit. Investigation of hydrocyclone efficiency from a classification point of view indicates that the separation of coarse and fine molybdenite minerals by this device has low efficiency. The volume frequency of fine-grained particles (−10 µm) at the inlet load, overflow, and underflow of the hydrocyclone is 40%, 45%, and 35%, respectively. As can be seen, the volume percentage of particles less than 10 µm in the overflow is about 10% higher than the underflow; this indicates the poor performance of the studied hydrocyclone. Comparing the distribution of coarse particles in the inlets and outlets of the hydrocyclone, it can be seen that the hydrocyclone has not performed well in transferring coarse particles to the underflow; significant amounts of particles larger than 50 µm have been observed at both underflow and overflow outlets. As mentioned, molybdenite particles have cleavage due to their unique crystalline structure and coarse-grained planar particles will be generated during comminution. Based on the literature, classification tests using a hydrocyclone and cyclosizer have shown that coarse-grained fractions of planar particles will not necessarily be recovered to the tailings. This problem is especially evident in cases of high-speed input load to the classifier (Kashiwaya et al. 2012). The release of coarse planar particles from the hydrocyclone overflow has also been reported for other planar particles such as mica (Wills and Napier-Munn 2006).

The effect of particle shape parameter on the efficiency of classification-dewatering devices

To investigate the effect of the particle shape parameter of the minerals present in the inlet load to the molybdenum processing circuit on their behavior in the dewatering and settling process in the thickener, as well as their classification and settling in the hydrocyclone, microscopic studies have been performed on all samples. The results of these studies are presented below.
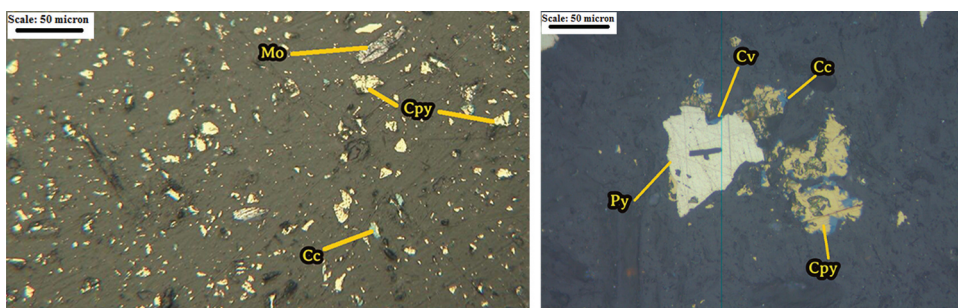
Figure 3. Distribution of copper sulfide minerals and molybdenite in the underflow of T-A (Cpy: chalcopyrite, Py: pyrite, Cc: chalcocite and Mo: molybdenite) – Reflected light photomicrographs in plane-polarized light (PPL).

A) Primary thickener or Copper-Molybdenum Concentrate (code T-A): Thickener *T*-A underflow incorporates minerals called chalcopyrite, pyrite, chalcocite, molybdenite, covellite, and a small amount of bornite. Figure 3 shows images of the distribution of these minerals in the thickener *T*-A underflow. The dimensions of the mentioned minerals are different which warrants pyrite larger size in comparison to most of the copper sulfide and molybdenite minerals in the sample. From a dimensional range standpoint, the particle size of chalcopyrite is observed in a larger range compared to pyrite (i.e., much smaller to larger than pyrite). Pyrite particles are closer in size to each other. Molybdenite particles do not have significant interlocking with other minerals, and their blade-shaped crystals have reached the desired degree of liberation. In general, most minerals are liberated, and only in some cases is there a slight locking between chalcopyrite and chalcocite and, to a lesser extent, chalcopyrite with covellite. Therefore, it is expected that a good separation between copper and molybdenum minerals will be achieved via the flotation process.

As mentioned, the molybdenite mineral particles in the load entering the circuit (thickener *T*-A underflow) have irregular blade shapes, while the copper mineral particles and other existing particles have more regular shapes (identical dimensions) as shown in Figure 4. During the settling process in the thickener, irregularly shaped particles settle at a slower rate than granular particles (granular-same dimensional) due to the lack of symmetrical and geometric shape. Therefore, it can be stated that the settling rate of molybdenite particles is lower than that of copper and they need more retention time to settle. Because in irregular shapes (amorphous particles and planar molybdenites) decreasing the surface area of the sphere and increasing the predicted surface area increases the elasticity. So, they tend to orient and take different paths in a preferred path during their fall. This optimal orientation is unpredictable and depends on the position of the center of gravity of the particles relative to the center.
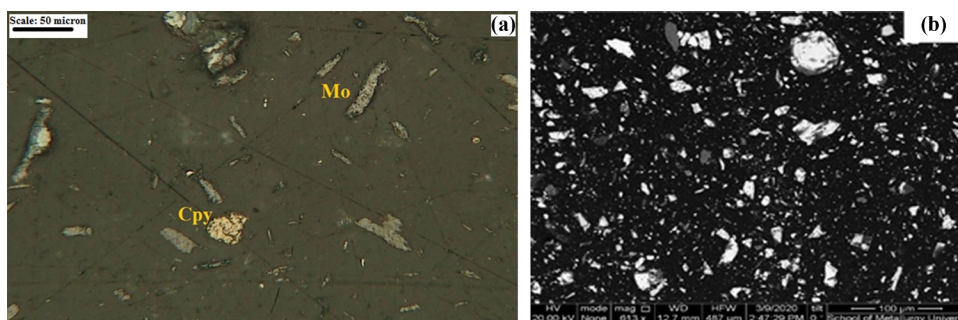

Figure 4. Shape and interlocking mode of minerals present in the underflow of *T*-A (Cpy: chalcopyrite, Mo: molybdenite). A) Reflected light photomicrographs in plane-polarized light (PPL), B) BSE photomicrograph.
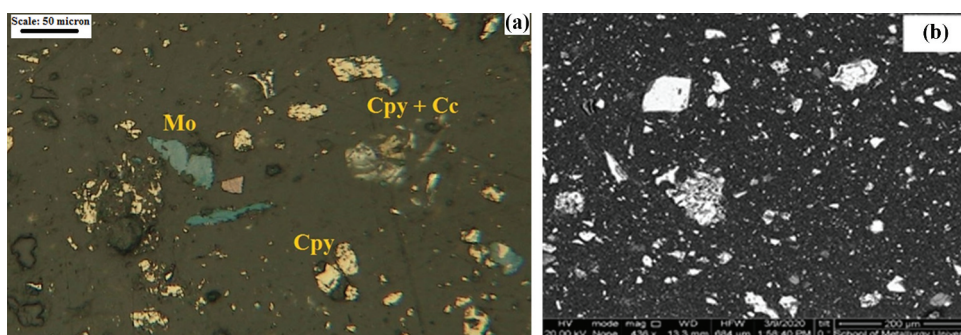
Figure 5. Distribution of minerals and interlocking between them in the T-B (Cpy: chalcopyrite, Cc: chalcocite and Mo: molybdenite), A) Reflected light photomicrographs in plane-polarized light (PPL), B) BSE photomicrograph.

B) Copper concentrate thickener (code T-B): The minerals in thickener T-B (or molybdenum flotation tailings) are copper sulfides with a predominance of chalcopyrite. According to Figure 5, approximately 1% of the molybdenite in the thickener T-B underflow is composed of free molybdenite blade-shaped particles. Due to their small size and mass, these particles moved with the water flow pattern and as a result, they did not collide with the air bubble during flotation and were transferred to the tailings.

C) Molybdenum plant middle thickener (code T-C): Microscopic studies of the input load to the T-C thickener and its overflow and underflow have indicated that coarser particles have entered the thickener overflow. Microscopic images of these sections are shown in Figure 6. Based on the analyzes, the grade of copper and molybdenum in the thickener overflow sample was 5% and 20.50%, respectively, and particles with large size and molybdenite planar particles can be observed in these sections. The particles that reach the thickener overflow have an almost uniform PSD. The passage of coarse particles and molybdenite planar particles to the overflow can be attributed to their low settling
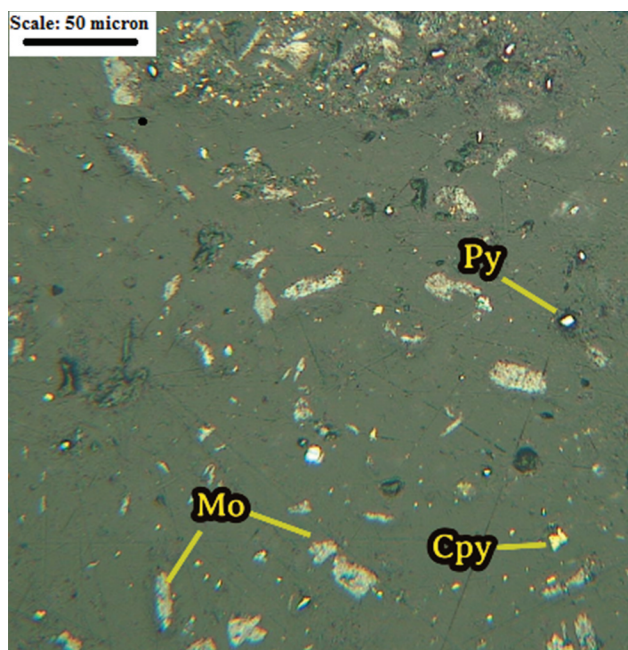

Figure 6. Distribution of minerals in the overflow of *T*-C (Mo: molybdenite, Cpy: chalcopyrite, Py: pyrite, Cc: chalcocite).
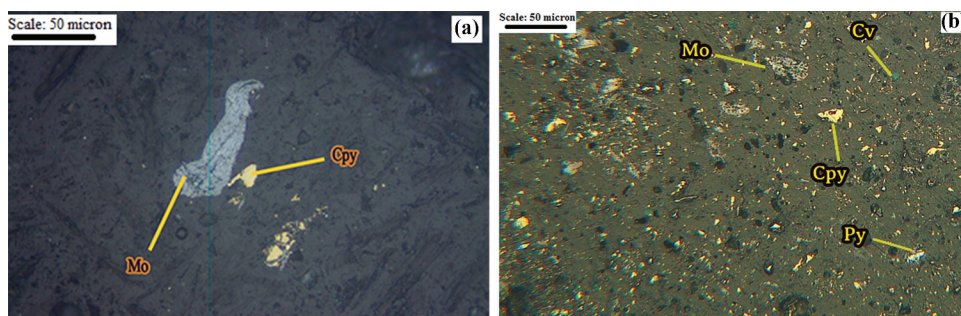
Figure 7. A) Molybdenite liberated particle B) distribution of minerals in the underflow of T-C (Mo: molybdenite, Cpy: Chalcopyrite, Py: pyrite).

rate due to changes in the surface charge of molybdenite particles in the planar state relative to fine-grained particles. The underflow cross-sectional (Figure 7) also shows the path of fine-sized particles to the underflow. In contrast to the molybdenum, the copper grade in the underflow is about twice that of the thickener overflow. Minerals in the middle thickener underflow are abundant, including molybdenite (≈40%), chalcopyrite (≈37%, of which 34% is free and ≈4% is interlocked with gangue), pyrite (≈13%), covellite (≈2%), and bornite (≈0.6%), respectively. The molybdenum grade of more than 20% in the thickener overflow and its comparison to the feed and underflow grade indicates the transfer of a significant part (about 0.04 wt. %) from the molybdenite mineral to the thickener overflow. The inherent floatability of molybdenite is related to its textural properties such as flatness, particle roundness, longitudinal elongation ratio, and smooth surfaces (Bahrami et al. 2020). The flatness and elongation of these particles reduce their settle-ability. Hence, the settling behavior of molybdenite is the result of a combination of inherent flotation properties and particle morphology (shape and size). Molybdenite particles with a higher aspect ratio (ratio of the major axis to the smaller axis) have a better chance of making their way to the thickener overflow. On the other hand, for molybdenite particles, the surface-to-edge ratio is a function of particle size and decreases for fine particles. Therefore, smaller particles have less hydrophobicity than larger particles and will settle more easily. The PSD diagrams of the input load and output of the intermediate thickener (Figure 3) also confirm this.

Middle thickener (*T*-C) in molybdenum processing plant has strategic importance and position. The concentrate of the early stages of flotation (cleaner No. 2) after entering the T-C thickener and increasing the solid mass percentage is directed to the milling process and then the flotation cells (cleaner No. 3). The input pulp to this thickener has a solid percentage of 10.82%, which after settling, underflow and overflow with a solid percentage of about 42% and 0.04%, respectively, are removed from it. Based on the grade analysis performed on thickener T-C underflow, the grade values of Mo, Cu, and Fe elements are 15.20%, 18.02%, and 17.57%, respectively. Due to the grade of molybdenum being 15.20%, this product cannot be supplied as a final concentrate, and it is necessary for reprocessing (cleaner flotation steps). Thus, the thickener T-C underflow enters the ball mill to grind and release more copper minerals from molybdenite (Figure 1). In thickener T-C, adjusting the solid percentage of feed entering the mill and PSD of the input load, in addition to the efficiency of the milling process, is very effective on the floatability and flotation rate of molybdenum (cleaner stages). Studies of the degree of liberation of molybdenite mineral in thickener T-C underflow indicate that this mineral has a good degree of liberation (about 98%). Therefore, milling leads to finer molybdenite particles and does not significantly change their degree of liberation, i.e., at this stage of comminution, molybdenite particles and copper sulfides have become smaller and transformed into fine particles. In addition to increasing energy consumption in the mill, the production of fine particles will hurt the flotation process and reduce flotation efficiency. By reducing the particle size of molybdenite, the surface-to-edge ratio decreases, and as a result, its hydrophilic properties increase, which reduces its

floatability. Another issue with the T-C thickener at the molybdenum plant is the lack of the molybdenum planar particles settling and their transfer to the overflow. The middle thickener overflow is notable from the molybdenum content standpoint due to its molybdenum content with a grade of about 20.50% and a solid percentage of about 0.04%. The T-C thickener overflow is utilized as wash water in the process, which due to the presence of molybdenite particles leads to choking in the water transfer pipes. Considering the T-C thickener position, it is not possible to use flocculants (typically starch flocculants used in this industrial unit) to precipitate floating molybdenite particles. Because the use of flocculants due to reducing the contact angle and trapping of molybdenite particles will lead to a sharp decline in recovery.

D) Molybdenum concentrate thickener (T-D code): In T-D thickener, molybdenite minerals, mainly in the form of free blade-shaped particles, which are rarely interlocked with other minerals and can be seen in different dimensions and proper purity (Figure 8). Particles of chalcopyrite and pyrite minerals are also found in the free form. The presence of copper mineral particles in molybdenum concentrate can be attributed to the lack of proper classification control in the circuit. In addition, the lack of optimal depressing of copper ores during flotation is a reason for the transfer of copper mineral particles to molybdenum concentrate. As mentioned in the previous section, particles of copper minerals have been observed at the thickener output of molybdenum concentrate. Two solutions can be utilized to solve this problem. In the first solution, the T-D thickener can be replaced with a hydrocyclone. The second solution is to install a hydrocyclone before the pulp enters the primary circuit shown in Figure 1 and separate the coarse and fine particles. By applying this approach, in addition to preventing the production of fine particles due to excessive comminution of minerals and therefore their recovery to molybdenum concentrate, energy consumption will be significantly reduced. Because molybdenite is an anisotropic mineral, its surface charge varies in different directions of molybdenite crystals. Therefore, the shape and size of the particles are one of the most important parameters in their settleability during the dewatering process as well as other downstream processes such as flotation.

E) Hydrocyclone of Molybdenum plant: Concentrate of cleaner No. 4 molybdenum flotation cell (Figure 1) with 39.34% molybdenum grade and 4.94% and 10.34% copper and iron grade, respectively, should be refloated to achieve a higher grade. In this regard, with the introduction of this concentrate into the hydrocyclone with a cut size of 38 μm, the underflow outlet enters the closed circuit ball mill for regrinding. In addition to reducing energy consumption in the milling process, the proper operation of this hydrocyclone is effective on downstream processes such as flotation, dewatering, and filtration, due to changes in product particle size. Accurate classification reduces the fine particles in the final product (Morrell 2008), which improves flotation recovery. It is obvious that as the amount of fine particles increases, flotation recovery decreases because the fine particles are less likely to collide with the air bubble and float slowly (Miettinen, Ralston, and Fornasiero 2010). Dewatering processes
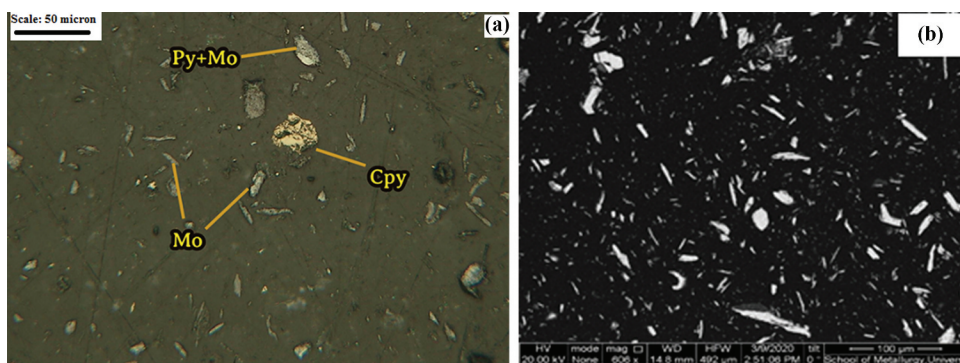

Figure 8. Types and distribution of minerals in T-D (Cpy: chalcopyrite, Py: pyrite, and Mo: molybdenite), A) Reflected light photomicrograph in plane-polarized light (PPL), B) BSE photomicrograph.
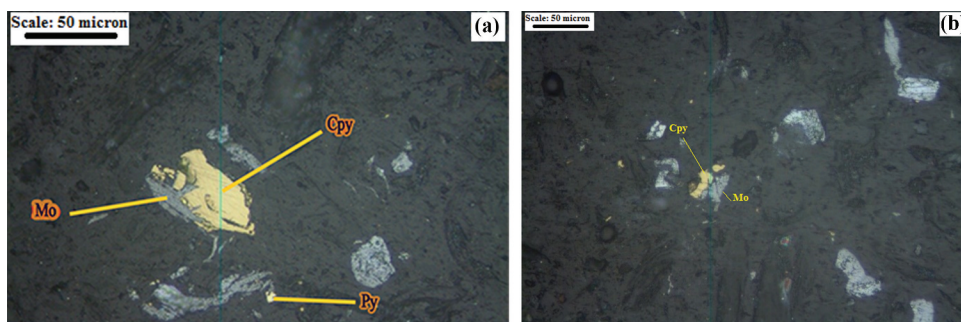
Figure 9. A) Distribution and B) interlocking of minerals in hydrocyclone underflow (Mo: molybdenite, Cpy: Chalcopyrite, Py: pyrite).

will also have better efficiency due to the optimal performance of the hydrocyclone and reduction of over-grinding and the specific area of the particles (Jankovic, Valery, and Sonmez 2013). Microscopic studies indicate that the minerals present in the hydrocyclone underflow are abundant, which by the order of frequency are, free molybdenite minerals in the form of blades and polygonal particles (Figure 9), free chalcopyrite minerals interlocked with gangues, and free or locked pyrite particles. As mentioned, the cut size of a hydrocyclone in a closed circuit ball mill is 38 μm, but according to the microscopic images of the hydrocyclone underflow sample, fine particles are also observed in this sample, which is due to the inefficient hydrocyclone performance. Product homogeneity is a key factor for more desirable flotation, thickener dewatering, filtration, and tailings accumulation. Classification sharpness in hydrocyclones reduces the number of fines and coarse particles in the product, which leads to a reduction in the consumption of chemicals. Therefore, there will be a reduction in the amount of coarser particles and trapping of liberated particles by very fine particles and thus reducing their waste in the downstream processes like floatation (Albuquerque, Valine, and Wheeler 2011). According to the diagrams in Figure 2 (PSD feed-overflow-underflow of the hydrocyclone), these diagrams show the inefficient performance of the hydrocyclone device in the separation of fine particles and their classification. According to the PSD diagram, d_{90} of feed, hydrocyclone overflow, and underflow are 53.17, 52.56, and 54.39 μm, respectively. On the other hand, by measuring the solid percentage of feed (approximately 12%) and underflow (approximately 15%) of the hydrocyclone used for dewatering and particle size control, it can be said that this device from the dewatering process standpoint, did not perform well. Given the above, the low solid percentage of input feed and the abundance of fine particles in the feed can be considered factors for poor performance in the milling process.

Conclusion

The structure of the molybdenite mineral due to the arrangement of molybdenum and sulfur layers with strong covalent bonds, and successive layers of sulfur atoms with weak van der Waals bonds formed an anisotropic crystal structure for this mineral, causing it to behave distinctively in different faces. Therefore, during the comminution process planar molybdenite particles in different dimensions are generated, which have unique behaviors in other processes such as classification and dewatering. Due to the multiplicity of classification and dewatering devices including hydrocyclones and thickeners in the molybdenite processing circuit, the effect of the shape and particle size of this mineral on the operation mechanism of these devices is imperative. The proper efficiency and effectiveness of these devices will have an actual impact on downstream processes.

This study that conducted on four thickeners in the molybdenum processing circuit, showed molybdenite particles, due to their unique planar shape, will not necessarily be transferred to the thickener underflow during dewatering processes, even in coarse-grained dimensions (>50 μm). The

presence of particles larger than 50 μm in the thickener overflow, in addition to the reduction of returned water quality, has led to problems such as the clogging of water pipes. On the other hand, due to the comminution process on the underflow of some of the existing thickeners, grinding smaller molybdenite particles will produce fine particles (<10 μm) and thus increase energy consumption in the milling process, as well as reduce flotation efficiency. Leakage of molybdenite planar particles from the hydrocyclone overflow at high inlet load rates, due to the increase in the amount of circulating load, and as a result, the production of fine particles in the hydrocyclone-mill circuit, harms grade and recovery (separation performance) of flotation. In general, the efficiency of the classification and dewatering system due to the shape and size of molybdenite particles has led to a decrease in the efficiency of the flotation circuit of this mineral.

It is suggested that in future studies, by modeling the particle separation processes in the hydrocyclone, and the settling in thickener, the effect of particle shape and size on the efficiency of other processes (grinding and flotation) should be quantitatively investigated.

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