

# Modification of mineral processing circuit in Arjin mine through a mineralogical study: magnetic separation and reverse flotation

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## Abstract:

The current mineral processing circuit of the Arjin iron mine faces serious problems regarding its reduced efficiency. In the present research, the concentrator circuit of the Arjin mine was modified through mineralogical study and other laboratory approaches magnetic separation, and flotation tests. The results verified that the feed contained magnetite as a valuable mineral with a degree of liberation of about 91  $\mu\text{m}$ . The magnetic separation and flotation tests were conducted to modify the circuit by measuring the iron recovery, sulfur, and iron contents in the obtained concentrates and tails. The magnetic separation tests with a magnetic field strength of 1000 Gauss were carried out on the initial feed with different  $d_{80}$  to determine the influence of particle size. The results verified that the feed with  $d_{80} = 120 \mu\text{m}$  could be considered the best feed size for magnetic separation. The sulfur content was then reduced from 0.99% to 0.05% in the final concentrate of reverse flotation as a desulfurization step. Based on the results, the proper circuit included reverse flotation and magnetic separation consisting of rougher, cleaner, and re-cleaner with the field intensities of 2500 G in the rougher and 800 G in the cleaner and re-cleaner steps. Finally, the total iron content was improved from 58% to 68.1%, and the recovery percentage was raised from 65% to 83.39% by the applied modifications.

**Keywords:** Geometallurgy; Mineralogy; Iron ore; Magnetic separation; Reverse flotation; Desulfurization

## 1. Introduction

Iron is the 4<sup>th</sup> most abundant element in the earth's crust (5% of the total) after oxygen, silicon, and aluminum (Lutgens et al., 2011). Iron has been widely used in various industries due to its unique properties, such as strength, ductility, flexibility, recyclability, and low cost (Clout and Manuel, 2015). In 2021, steel production in Iran reached 28.5 million tons, with the rank of 10 among all steel-producing countries (worldpopulationreview.com web). Currently, high-grade hematite, goethite, and magnetite ( $\text{Fe}_3\text{O}_4$ ) ores supply steel-producing plants with growing demand (Baawuah et al., 2020; Abbasian et al., 2022).

Magnetite is an iron oxide mineral found in magmatic and

sedimentary deposits (Clout and Manuel, 2015). The most common technology used for processing magnetite is low-intensity magnetic separation (MS) (Karmazin et al., 2002; Ouyang et al., 2013; Xiong et al., 2015; Ousta et al., 2024). The first attempts to process magnetite ores by using permanent magnets date back to the 17<sup>th</sup> century, as done by Derkach (Bikbov et al., 2004). Depending on the mineralogical properties, the mineral processing circuit for iron ore processing usually consists of several stages of low-intensity magnetic separation (LIMS) or a combination of MS with reverse flotation (Karmazin et al., 2002; Saravari et al., 2021; Yu et al., 2016; Song et al., 2019; Hosseini-Nasab and Rezazadeh, 2022; Nazari et al., 2023). It is noteworthy that MS has such advantages as handling a high tonnage of



product of reverse flotation, the final concentrate, and the final tail of the modified circuit.

MS and flotation tests were then conducted on a laboratory scale by using Davis Tube (OPEK-Co SI-2102 type two) and Denver flotation machine (Daneshfaravaran DF-FC-1500), respectively. To investigate the effect of particle size on the MS, 10 samples weighing 10 g (100 g) were selected from the milled samples and entered into the Davis tube device. The MS with a magnetic field of 1000 G was then performed on the samples as a rougher step. According to the results of magnetic separator tests, the proper particle size was determined for the subsequent flotation and MS tests. In the flotation step, reverse flotation with the rougher and scavenger arrangement was applied to remove sulfide minerals such as pyrite and other Cu-bearing minerals. The flotation conditions and chemical agents used are listed in Table 1.

The obtained tail from the rougher step was fed to the scavenger step in which the mixer speed was increased from 1200 to 1500, and collector dosage was decreased by 50% with pH = 8.5 and Eh = -930. After 5 minutes of frothing, the change of froth color from sludge to white indicated that the tail minerals such as pyrite were not retained. Finally, the concentrates and tails were dried and weighed before analysis. The research steps were 1) grinding tests, 2) initial MS experiments, 3) reverse flotation, and 4) final MS experiments. Through mineralogy and chemical composition analyses, the steps were analyzed, and their results were utilized in the modification of the current circuit.

The chemical composition of the samples was determined by coupled plasma optical emission spectroscopy (ICP-OES VARIAN 735ES) and the Potassium dichromate titration method, for FeO measurement. Also, X-ray diffraction analysis (XRD) was conducted by a Philips DW3710 instrument by applying Cu K $\alpha$  radiation at 50 kV and 250 mA.

### 3. Results and discussion

The chemical composition analysis indicated that the major constituent elements of the Arjin mine were iron and silica

(Table 2). The FeO and Fe (Total) were 16.9% and 39.5%, indicating that the ore contained about 54.51% magnetite without any hematite. Also, the main unwanted elements in the sample were S and SiO<sub>2</sub> with concentrations of 0.99% and 18.9%, respectively. The XRD analysis (Table 3) confirmed the chemical composition analysis when the magnetite content was 55%. The mineral contents obtained from qualitative analysis of XRD were not precise enough, but the order of their abundance could provide more evidence for the following findings, indicating that magnetite is a major phase. Although the precision of XRD and ICP-OES analyses was different, the magnetite content was approximately equal in both analyses. Based on the results, magnetite was identified as the main magnetic mineral in the mine. The XRD analysis also demonstrated that gangue minerals were talc, calcite, quartz, dolomite, chlorite, pyrite, and mica. Among the gangue minerals, dolomite and quartz were the other major constituent phases with contents of 11% and 12%, respectively.

Subsequently, the degree of liberation for the present minerals in the iron ore was obtained through the microscopic determination method (Table 4). The selected sample was crushed and milled with laboratory crushing machines to a size of -500  $\mu$ m. A 200 g of the milled powders was sieved by 75, 106, 180, 250, and 500  $\mu$ m screens. The results proved that the degree of liberation for the magnetite in the iron ore was 86.57% in 91  $\mu$ m (Table 4).

In the beginning, an attempt was made to choose the proper milling time and also, to study the influence of particle size on the MS step as a main separation process. For this reason, a 2 kg sample was milled by using a dry rod mill on the laboratory scale. After milling at different times of 5, 15, 30, and 45 min, sieving was performed by 45, 75, 106, 180, 250, and 500  $\mu$ m screens. The particle size distribution of the feed and milled powders is presented in Fig. 2. As can be seen in Fig. 2 and Table 5, d<sub>80</sub> and d<sub>50</sub> were reduced with the milling time. In addition, the results proved that d<sub>80</sub> was decreased from 80  $\mu$ m in the 30 min milled sample to 77  $\mu$ m after 45 min milling. Therefore, 30 min milling could

**Table 1.** Conditions and chemical agents used in flotation.

Solid mass	Water mass	Collector type	Frother type	Temperature	pH
600 g	2400 g	Flomin & Z11	A75 & A65	25 °C	7.41

**Table 2.** Chemical composition of initial feed obtained from Arjin mine.

Elements	K <sub>2</sub> O	FeO	Fe Total	CaO	S	SiO <sub>2</sub>	MgO	P	MnO	TiO <sub>2</sub>	LOI
Conc. (%)	0.9	16.9	39.5	7.3	0.99	18.9	3.5	< 0.05	0.14	0.1	5.9

**Table 3.** Constituent minerals of Arjin mine obtained by XRD analysis.

Phase	Chlorite	Talc	Dolomite	Magnetite	Quartz	Calcite	Pyrite	Mica - Illite
Conc. (%)	1	2	11	55	12	7	2	9

**Table 4.** Degree of liberation for magnetite in Arjin mine.

Particle size range ( $\mu$ m)	+250 -500	+180 -250	+106 -180	+75 -106
Degrees of liberation (%)	38.12	47.73	63.93	86.57

**Table 5.** The  $d_{80}$  and  $d_{50}$  values of 5, 15, 30, and 45 min milled samples.

Milling time	45 min	30 min	15 min	5 min
$d_{50}$ ( $\mu\text{m}$ )	57	60	65	130
$d_{80}$ ( $\mu\text{m}$ )	77	80	120	300

be considered as the optimum milling time because more milling meant more energy consumption, higher cost, and improved fine production.

The MS tests began by using a Davis tube with 1000 G magnetic field intensity to study the influence of the particle size on MS. The MS tests were evaluated by calculating the feed percentage entering the concentrate and tail (Fig. 3). Due to the increasing liberation of valuable minerals from tail minerals, the concentrate weight was decreased by increasing the milling time from 5 min to 15 min.

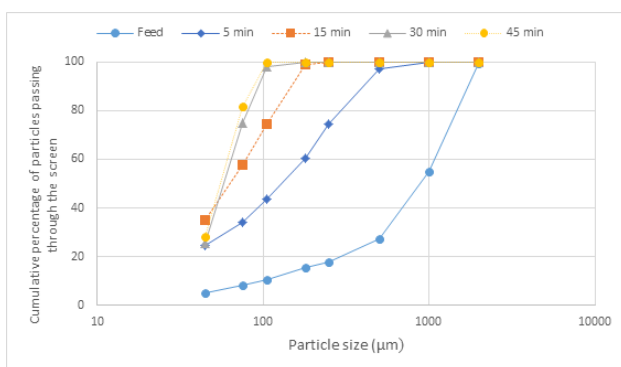
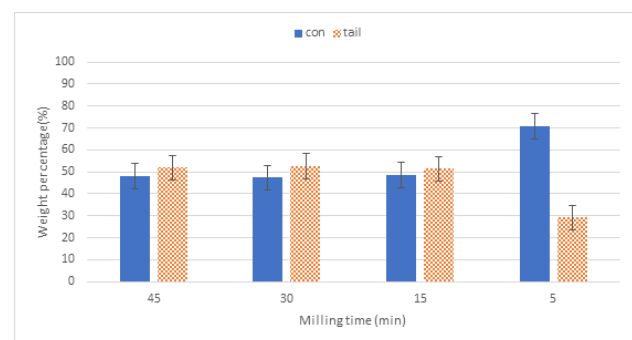
Additionally, no significant change was observed in concentrate and tail weight with reducing  $d_{80}$  to 80  $\mu\text{m}$  after 30 min milling and also to 77  $\mu\text{m}$  after 45 min milling, despite the liberation degree improvement. The fine tail particle transferred to the concentrate could be responsible for the case. This was confirmed by mineralogical studies showing the gangue minerals in the final concentrate. Although more milling could improve the final concentrate properties (Hosseini-Nasab and Sadeghi, 2020), the 15 min milling ( $d_{80} = 120 \mu\text{m}$ ) was considered as a proper milling time based on the result of the initial MS test (Fig. 3), avoiding the disadvantage of more milling.

After the initial MS test, the obtained samples from 15 min milling ( $d_{80} = 120 \mu\text{m}$ ) were desulfurized by reverse-flotation through rougher and scavenger steps, as cited before (Saravari et al., 2021). As can be seen in Table 6, the ICP-OES results revealed that sulfur and phosphor content was decreased to less than 0.05% in the scavenger product with a  $\text{SiO}_2$  content of 17.6%. According to the findings,

the FeO content was increased from 16.9% in the feed to 19.20% in the scavenger tail. In addition, the results indicated that iron was lost in the reverse flotation step, while the concentrate was about 9.51% FeO, and the total iron recovery in the flotation step was 86.62%.

The final tail obtained from the reverse flotation was considered for the MS tests with 2500 G and 800 G magnetic field intensity. To produce a concentrate with a higher iron content, the sample was processed according to the modified circuit presented in Fig. 4. The processing circuit of magnetic separation consisted of three MS steps; rougher (2500 G), cleaner (800 G), and re-cleaner (800 G). The final tail was produced from the rougher while the final concentrate was the re-cleaner product. The Fe content in the tails and concentrates of these steps was recorded, as can be seen in Fig. 4 and Table 7.

According to the ICP-OES results, the final concentrate had a total iron content of 68.10%, and consequently magnetite content would be 93.98%. Also, the final tail had total iron and  $\text{SiO}_2$  contents of 3.17% and 44.3%, respectively. The amount of S and P in the concentrate was reduced to less than 0.05% and the LOI content was below 0.05%. Also, the total iron recovery of the MS circuit was calculated to be 96.47%, where f, c, and t were the iron contents in the feed, final concentrate, and final tail (Fig. 4). The results also proved that the recleaner concentrate could be considered as the final concentrate wherein the iron grade in the re-cleaner and the cleaner concentrate is close together. Regarding the analyses, the mineralogical study was con-

**Figure 2.** Cumulative percentage of the particle size distribution of initial feed, 5, 15, 30, and 45 min milled samples.**Figure 3.** Variation of feed to concentrate and tail percentage after 1000 G MS with different milling times of 5, 15, 30, and 45 min.**Table 6.** The chemical composition of the rougher-scavenger concentrate and tail obtained from the reverse-flotation test.

Cont. (%)	$\text{SiO}_2$	FeO	Fetotal	$\text{K}_2\text{O}$	S	P	LOI
Feed	18.9	16.9	39.5	0.92	0.99	< 0.05	5.93
Scavenger tail	17.6	19.20	44.88	0.49	< 0.05	< 0.05	6.07
Concentrate	25.2	9.51	22.24	2.86	4.50	< 0.05	4.83

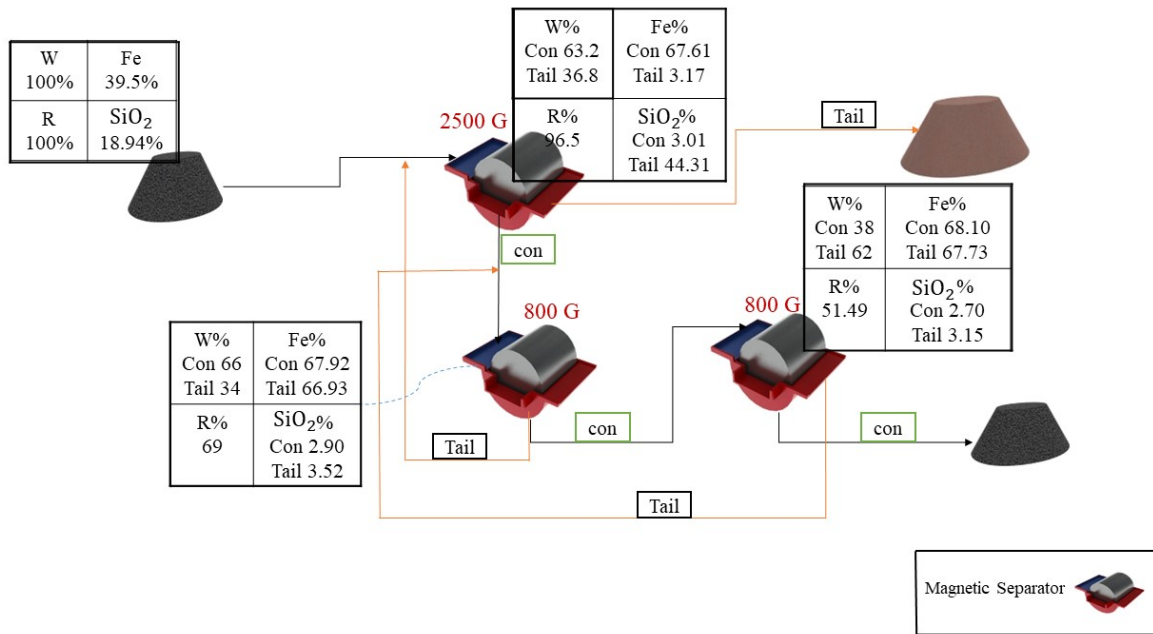


Figure 4. The MS circuit studied in the present research work.

Table 7. ICP-OES results of the rougher-scavenger concentrate and tail as obtained from the final MS tests (cont. %).

Sample	SiO <sub>2</sub>	Fe total	LOI
Reverse flotation product (rougher tail)	17.6	44.88	6.07
Rougher concentrate (2500 G)	3.0	67.61	< 0.05
The final tail	44.3	3.17	21.53
Cleaner concentrate (800 G)	2.9	67.92	< 0.05
Cleaner tail (800 G)	3.5	66.93	< 0.05
The final concentrate	2.7	68.10	< 0.05
Recleaner tail (800 G)	3.1	67.73	< 0.05

ducted on the Feed, flotation product, final tail, and final concentrate samples through Reflected and Transmitted light photomicrographs in plane-polarized light (PPL) and cross-polarized light (XPL). The findings have been described in Figs. 5 to 8.

Fig. 5 (a) Magnetite and gangue minerals of dolomite, quartz, and talc in the feed sample (Transmitted plane-polarized light).

Fig. 5 (b) Magnetite and pyrite in the feed sample (Reflected plane-polarized light).

Fig. 6 (a) Magnetite with dolomite in the reverse flotation product (Transmitted plane-polarized light).

Fig. 6 (b) Magnetite in the form of fine and coarse grains scattered in the reverse flotation product (Reflected plane-polarized light).

Fig. 7 (a) Euhedral magnetite grains with the gangue minerals of quartz and calcite in the final tail (Transmitted plane-polarized light).

Fig. 7 (b) Free grain of magnetite in the final tail (Reflected plane-polarized light).

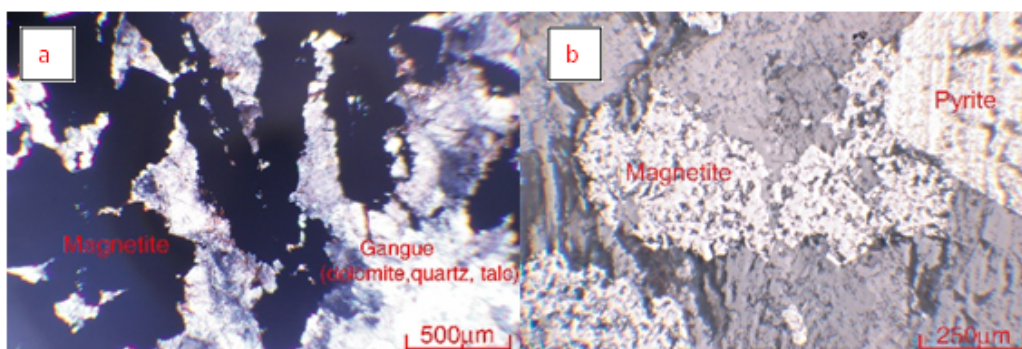
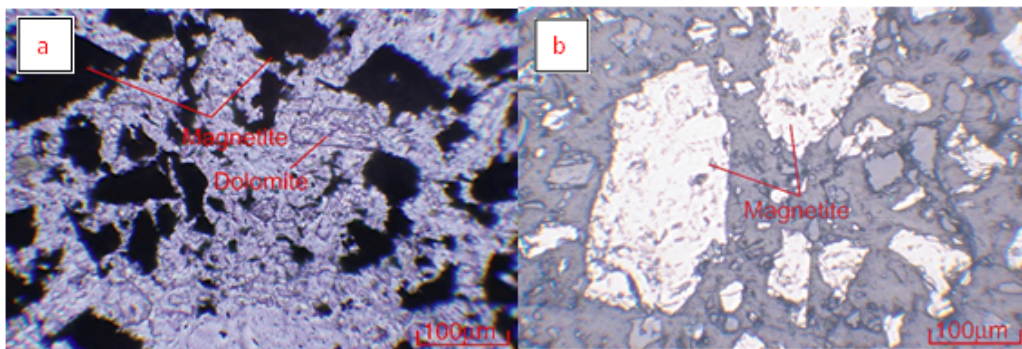
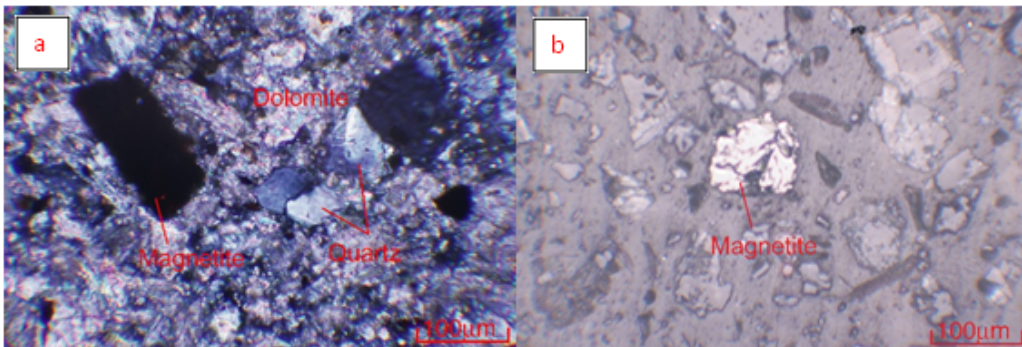


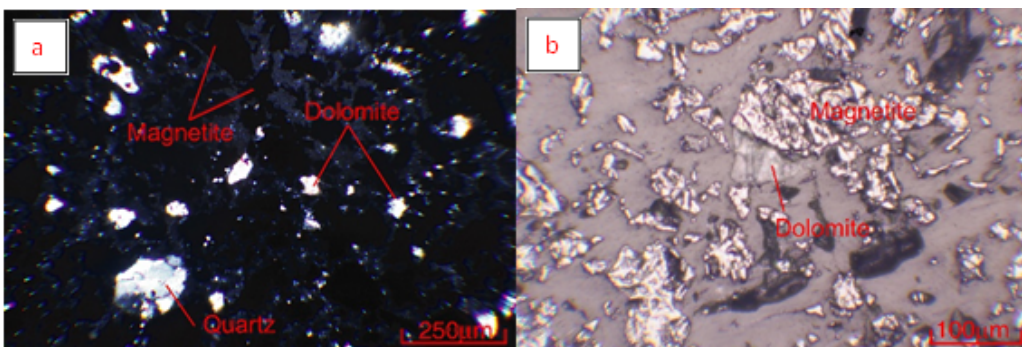
Figure 5. Transmitted (a) and reflected (b) light photomicrographs of the feed under (PPL).



**Figure 6.** Transmitted (a) and reflected (b) light photomicrographs of reverse flotation product (PPL).



**Figure 7.** Transmitted (a) and reflected (b) light photomicrographs of the final tail (PPL).



**Figure 8.** Transmitted (a) and reflected (b) light photomicrographs of the final concentrate.

Fig. 8 (a) Magnetite with the gangue minerals of dolomite and quartz in the final concentrate (Transmitted cross-polarized light).

Fig. 8 (b) Magnetite with the gangue mineral of dolomite in the final concentrate (Reflected plane-polarized light).

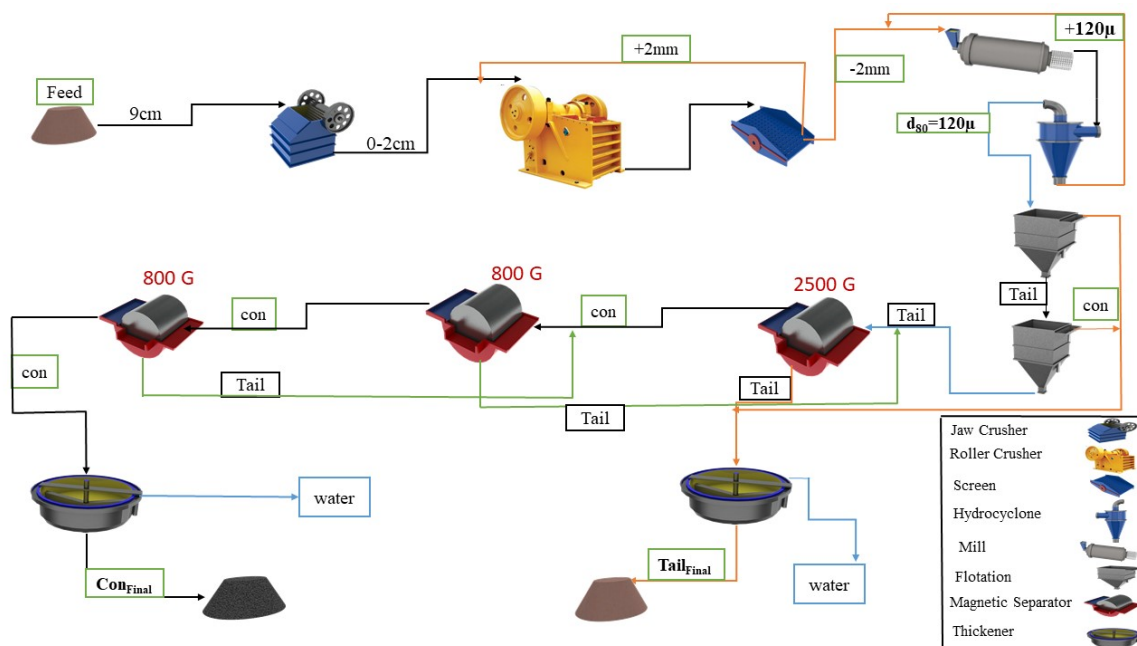
Based on the mineralogical study, the probable minerals existing in the samples are listed and shown in Table 8 and Figs. 5, 6, 7, 8. Magnetite was the main valuable mineral in the feed, tail, and concentrate samples, as identified in the polished thin sections. The gangue minerals detected in the feed and reverse flotation concentrate were dolomite, talc, quartz, pyrite, chlorite, and tremolite-actinolite. After MS, all the gangue minerals were removed from the feed and transferred to the final tail, while a small amount of them was observed in the final concentrate. The magnetite mineral was transferred to the final concentrate, except for a small amount that remained in the final tail.

Regarding the iron contents in the concentrate (50 – 58%)

and tail (9 – 12%) mentioned earlier, the proper separation of valuable minerals from the gangue ones would not occur in the present circuit. Consequently, reducing the size of the milling product from  $d_{80} = 250 \mu\text{m}$  in the present circuit to  $d_{80} = 120 \mu\text{m}$  in the modified circuit and exerting a reverse-flotation step would significantly improve the iron processing circuit performance. Accordingly, it was concluded that the modified circuit of the Arjin mine (Fig. 9) would be different from the present one (Fig. 1). The proposed circuit would consist of a crushing step for preparing a  $-2 \text{ mm}$  product as the feed for the milling step. The milling step would be continued to prepare a product with  $d_{80} = 120 \mu\text{m}$  for reverse flotation. The obtained product from reverse flotation would be processed through the three-step MS of rougher, cleaner, and re-cleaner to produce the final concentrate and tail.

**Table 8.** Mineralogy studies of the Arjin ore feed, flotation product, concentrate, and final tails of the modified circuit.

Sample	Important minerals in the polished section	Important minerals in the thin section
Feed hand sample	Valuable mineral: magnetite	Valuable mineral: magnetite
	Gangue opaque minerals: pyrite and limonite	Gangue minerals: dolomite, talc, quartz, pyrite
Reverse flotation product	Valuable mineral: magnetite	Valuable mineral: magnetite
	Gangue minerals: Pyrite	Gangue minerals: Dolomite, Talc, Quartz, Chlorite, Tremolite-Actinolite, Pyrite
The final tail	Valuable mineral: magnetite	Valuable mineral: magnetite (low)
	Gangue mineral: Pyrite	Gangue minerals: Dolomite, Talc, Quartz, Chlorite, Tremolite-Actinolite, Pyrite
The final concentrate	Valuable minerals: magnetite and hematite (very low)	Valuable mineral: Magnetite (most of the sample)
		Gangue minerals: Dolomite and quartz (low)

**Figure 9.** The final iron processing circuit proposed after performing modifications for the Arjin mine.

#### 4. Conclusion

The iron processing circuit of Arjin mine was modified through the mineralogical study, crushing and milling tests, reverse-flotation experiments, and magnetic separation runs. The following results were obtained from the studies, laboratory experiments, and the applied modifications. The results of the XRD test revealed that the magnetite content in the samples was 55%, which was approximately equal to that obtained by the ICP-OES analysis. Based on the results, the gangue minerals of the ore were talc, calcite, quartz, dolomite, chlorite, pyrite, and mica. According to the mineralogical study, the magnetite mineral was identified as the main valuable mineral along with gangue minerals such as dolomite, talc, quartz, pyrite, chlorite, and tremolite-actinolite. The gangue minerals were almost transferred from the feed to the final tail, while small parts of them could be detected in the final concentrate. The valuable mineral of magnetite as the main mineral in the final concentrate was separated from the gangue minerals. The degree of liberation of magnetite in the Arjin iron

ore was calculated at about 91 microns ( $+75 \mu\text{m} - 106 \mu\text{m}$ ) through the microscopic determination method. The primary milling and MS tests proved that 15 min milled feed with  $d_{80} = 120 \mu\text{m}$  could be considered for the reverse flotation and magnetic separation. By the application of reverse flotation for desulfurization before the magnetic separation, the S content was reduced from 0.99% to 0.05% in the reverse flotation tails. In addition, the total iron content was increased from 39.50% to 44.88% in the tail of reverse flotation as the feed of the magnetic separation. Based on the magnetic separation tests, more modification was proposed by designing three steps, namely the rougher (2500 G), the cleaner (800 G), and the re-cleaner (800 G) for the magnetic separation. The rougher tail was considered the final tail of the magnetic separation circuit and the re-cleaner concentrate was the final concentration. The iron content was increased from 39.5% in the feed of the magnetic separation step to 68.10% in the final concentrate, where the S and P contents were very low. The results, thus, indicated that more than 97% of the

final concentrate consisted of magnetite when the total recovery was about 83.4%. The results also proved that the modification could raise the iron content of the final concentrate from 58% in the present concentrate to 68.1% in the final concentrate of the modified circuit. The iron grade improvement could increase the product price from 52.8 /ton to 143 /ton (FOB Bandar Abbas-2021).

#### Authors contributions

All authors have contributed equally to prepare the paper.

#### Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

#### Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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