APPLICATION OF SAG MILL– BALL MILL GRINDING SYSTEMS IN COPPER MINES OF EASTERN SERBIA

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Abstract: *The current trend in comminution energy consumption shows an increasingly upward projection, which is likely to escalate into the future due to the need to grind ores, which are rapidly becoming low-grade and fine-grained, finer for liberation. Among the higher capacity unit technologies for grinding, SAG mill grinding has proven over the years to be an attractive and preferred technology and highly effective for grinding ore in a concentrator. The major acknowledged advantage of SAG mills is the massive throughput that can be achieved through a single unit. The ability to accept feed of up to 300 mm eliminates the need for crushing beyond the primary crusher.*

In recent years, copper mines in Serbia also followed a trend of moving from conventional to more innovative crushing and grinding processes.

This paper presents the basic characteristics of a typical SAG mill, its application in grinding circuits, and in more detail, emphasizes new technological schemes of grinding, and operating characteristics of SAG mills installed in Čukaru Peki, Veliki Krivelj and Majdanpek copper mines in eastern Serbia.

Key words: SAG MILL, GRINDING, EASTERN SERBIA MINES

INTRODUCTION

Comminution is a key unit operation in mineral processing and other allied industries. It is also the most capital-intensive unit operation in mineral processing and typically accounts for 30% to 50% of the total power consumption [1]. The current trend in comminution energy consumption shows an increasingly upward projection, which is likely to escalate into the future due to the need to grind ores, which are rapidly becoming low-grade and fine-grained, finer for liberation. For example, the global copper mining industry is predicted to consume 41.1 terawatt-hours (TWh) of power in 2025, an increase of 95.5% compared with 2013 [2,14,16].

Grinding, because it is normally the final stage of the comminution, takes on special importance and is often described as the key to successful plant operation [3]. The higher capacity unit technologies for grinding the ore such as AG, SAG, and ball mills, are well suited to processing low-grade ore at high volumes [4].

Among the higher capacity unit technologies for grinding, SAG mill grinding has proven over the years to be an attractive and preferred technology and highly effective for grinding ore in a concentrator. It is perhaps the only technology that works on every ore to which it is applied [5].

The major acknowledged advantage of SAG mills is the massive throughput that can be achieved through a single unit, with values exceeding 5000 t/h. The ability to accept feed of up to 300 mm eliminates the need for crushing beyond the primary crusher. The SAG mill can be linked to one or two large ball mills to complete a full-size reduction from run-of-mine (RoM) feed to flotation feed in three stages [6]. The use of AG/SAG milling has grown to the point where many existing plants are retrofitting them, whilst new plants rarely choose a design that does not include them [20].

CHARACTERISTICS OF SAG MILL

Grinding mills in which comminution takes place without grinding aids are known as Autogenous Grinding (AG) mills. These mills use large lumps of rock as the grinding media. Mills that grind hard ores with fracture characteristics that do not lend themselves to fully autogenous milling are charged with a small amount of steel balls to assist in the size reduction. These are known as Semi-autogenous Grinding (SAG) mills (Figure 1).

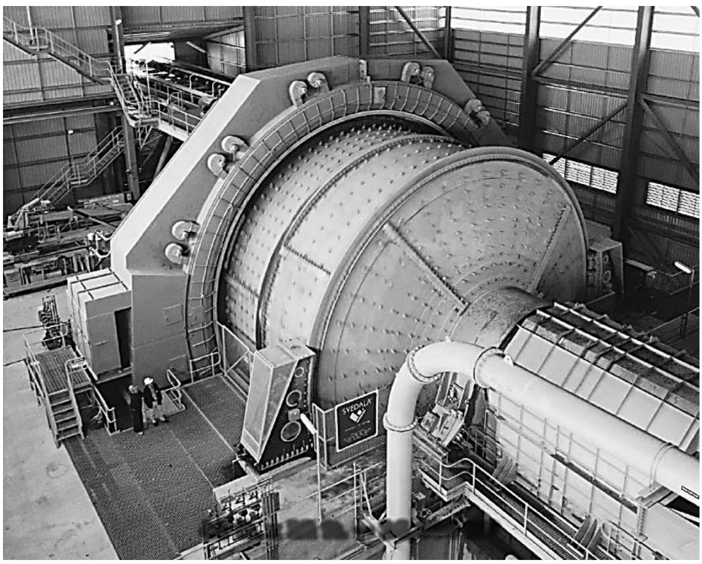

Figure 1, SAG mill (Diameter 12,1 m, length 7 m)

The disintegration and size reduction of ores in AG/SAG mills is brought about by a combination of impact, attrition, and abrasion forces during mill rotation (Figure 2).

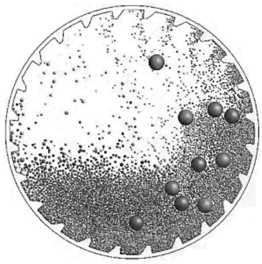

Figure 2, SAG mill cross-section

Particles at the toe of the mill charge receive the maximum impact forces from falling rocks and other grinding media. Particles in the body of the mill charge partly slide from different heights and are subjected to attrition and abrasion resulting in size reduction (Figure 3).

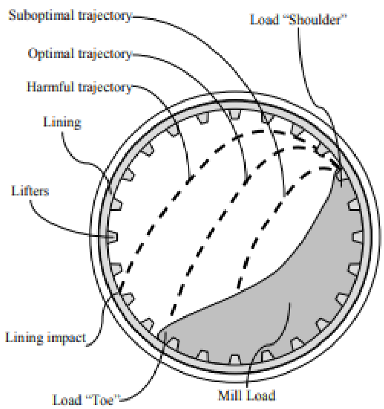

Figure 3, Possible trajectories of steel balls in a SAG mill [7]

The operation of AG/SAG mills therefore involves the use of cheaper grinding media as a replacement for expensive steel balls and rods which greatly affect the wear on liners. They are therefore less expensive to operate. It is necessary that the ore should provide a sufficient amount of lumps that would last for a reasonable time to act as the grinding medium. Since the breakage of ore in AG/SAG mills is mostly due to impact on particles and media from a height, these mills generally have a large diameter-to-length (D/L) ratio D/L = 1.5 - 3.0 (High aspect mills as shown in Figure 4). However this ratio varies and mills with large length-to-diameter ratios are also in use, eg. in South Africa. The Cadia Hill (Australia) wet SAG mill is 12.2 m in diameter with a 20 MW motor and in 2004 was the largest diameter mill in operation in the world. Mill sizes up to 13.4 m in diameter are considered feasible with current technology [8].

Most AG and SAG mills have slotted steel and rubber liners and are fitted with lifter bars. The liners are either waved or grid-type. The present tendency is to use composite liners with lifters at the feed end of a mill to initiate impact crushing followed by wave liners along the rest of the length of the mill. The basic object of liner design is to promote comminution by impact and attrition instead of abrasion.

The discharge ends are fitted with slotted grates acting as a diaphragm, which holds back the larger particles from discharging into the product stream.

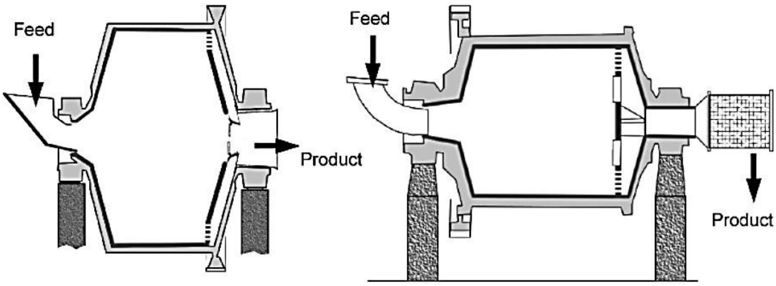

Figure 4, High aspect ratio SAG mill with grating and conical ends and square SAG mill with grating

DESIGN OF AG/SAG CIRCUITS

In designing a crushing-grinding circuit, the concentration of the mineral in ore and its downstream treatment is of prime importance. Equally important is the liberation size of the mineral, which determines the ultimate grind. The commonly used circuits for AG/SAG mills are:

1. open circuit with a trommel or screen as the classifier,
2. closed circuit with cyclone classifier,
3. open circuit with closed circuit ball mill, and
4. open circuit followed by a secondary crusher and then ball milling.

The first two types may be called single-stage operations while the last two are two-stage operations. Most AG/SAG mills operate in open circuits (Figure 5) when the product size is usually coarse. Usually, provision exists for installing a classifier like a straight screen, a trommel, or a curved DSM screen to remove critical-sized pebbles (scats). For finer and more uniform product, closed circuit grinding with classifiers, like a hydrocyclone, is usually employed (Figure 5) [19].

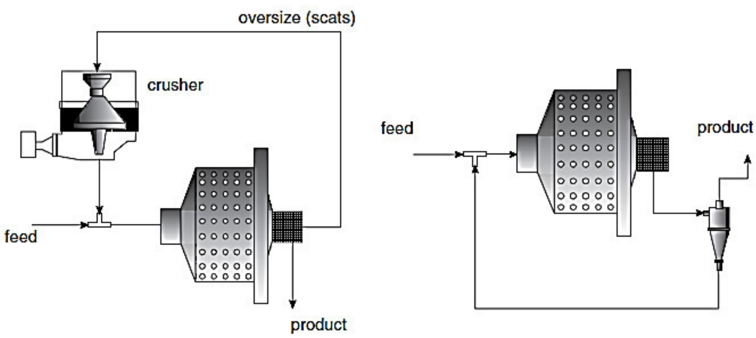

Figure 5, SAG mill circuit – with provision for scats recycle (left) and SAG mill in closed circuit (right)

A two-stage close circuit-grinding set-up with hydrocyclone is shown in Figure 6.

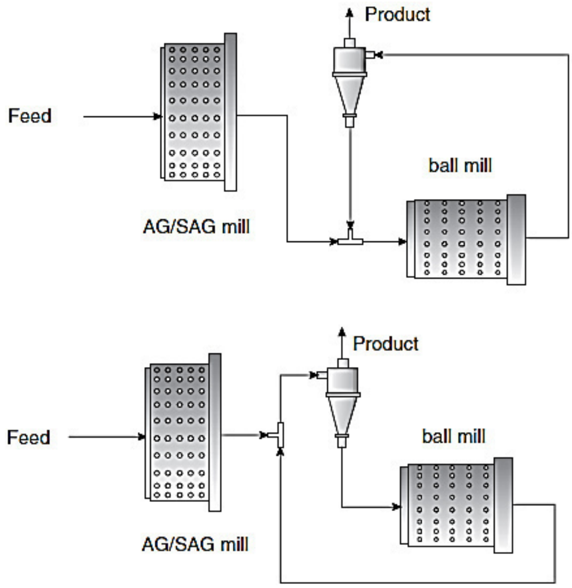

Figure 6, Two-stage AG/SAG – ball mill cicuits

The main problem in designing and operating an AG/SAG circuit is the tendency to build up the 25-50 mm fraction of the charge which hampers throughput. This specific size fraction that builds up in the mill is referred to as the critical size. Therefore pre-treatment of the feed should be such that the presence of this fraction is minimal. If the build-up of critical-sized pebbles is too great 50 - 90 mm slots are cut into the grate (pebble ports) to allow the scats to discharge from the mill. These scats are crushed before returning to the SAG mill or passing onto a ball mill in an ABC (Autogenous/Ball mill/Crusher) circuit (Figure 5) [9,17,18].

SAG MILL STRENGTHS AND LIMITATIONS

The SAG mill is a mechanically simple machine, yet with complex performance. The interactions between ore properties, load composition, design of the mill internals, power input, and breakage rates make the SAG mill the most difficult unit process to operate on most mine sites [6].

ADVANTAGES

The major acknowledged advantage of SAG mills is the massive throughput that can be achieved through a single unit. The ability to accept feed of up to 300 mm eliminates the need for crushing beyond the primary crusher. The SAG mill can be linked to one or two large ball mills to complete a full-size reduction from run-of-mine (RoM) feed to flotation feed in three stages. Usually, there are two ore feed conveyors, from the primary crusher to the primary ore stockpile and to the SAG mill plus one sump with two pumps to provide the full circuit materials handling transport. The simplicity of the process leads to a compact footprint, low operating costs (especially in terms of maintenance), and high reliability leading to high overall availability – exceeding 96%. This capability has transformed the ability of the mining industry to process massive low-grade ore bodies, some processing over 300 000 tons per day through a few parallel units.

LIMITATIONS

Build-up in critical size: It is well established from the earliest use of AG and SAG mills that the build-up of competent critical-size material, can drop throughput to half. This so-called critical size material grinds slowly, partially because it will selectively be the most competent in the feed but also due to the impact energy being too low to break this by impact. This results in a slow abrading of these rocks rather than breakage through impact.

To overcome this limitation, pebble ports were added to the discharge grates to remove this critical size, which was then sent to a recycle crusher for crushing to a smaller size before being returned to the mill. It is almost standard practice to install a SAG mill in the SABC (SAG, ball mill, crusher) configuration. A notable drawback of this practice is that the SAG mill product is coarser – moving the work downstream to the ball mill circuit. This has resulted in circuits with up to three ball mills per SAG mill.

Variable throughput and product: As the feed rocks form the grinding media, both the feed and grinding media size and fraction in the mill vary with feed size and competence. This results in a variable milling capacity in terms of throughput and product size expressed as medium-term drift in plant capacity plus short-term (minutes) variation in product size to recovery. Direct-feed flotation circuits are especially sensitive as they have no buffer capacity to smooth out this sometimes wide variation in grind size, resulting in variation and thus reduction in recovery. There are limited knobs to turn in order to respond to feed variability, speed for the large mills (really only a long-term variable), water (reduces mill efficiency when water ratio increased), mill filling (allowing the filling to build-up or fall – but often limited by power draw constraints), ball fraction (only a long-term variable), then as a last resort the mill feed rate. With all of these limited control knobs, the feed rate-product size varies leading to an inevitable variation in feed to flotation and thus recovery.

Low capacity for highly competent ores: When fed with extremely competent ores, having JK drop weight test values of A*b under 25, SAG mills lack the specific input energy to rapidly break the rocks, leading to slow abrasion. Although this produces a large amount of final fine product, this may be far finer than required thus rendering the mill ineffective in terms of throughput and energy utilization [6].

APPLICATION OF THE SAG CIRCUITS

Application of the SAG circuits is represented in large-capacity mines in many plants around the world. The advantages of this innovative process are reflected in its simplicity; it is a process that requires a smaller operating area, is characterized by a short construction period, the absence of dust due to the wet processing process, and a favorable working environment.

In the last 20 years or more, there has been a trend of moving from conventional to more innovative crushing and grinding processes. On the example of the Australian company Dominion Mining Limited, where SAB process equipment was installed alongside the already existing, traditional 3CB process equipment, on identical raw ore, the reasons for choosing new equipment could be clearly seen. First of all, the SAB methodology required lower investments. On the other hand, although the energy consumption was higher, the very characteristics of the mineral raw material (wearable, soft, and sticky ore) impose the need to use the SAB process in relation to the 3CB process, because the crushing of such raw material is very difficult [10]. When choosing a technological process scheme for the deGrussa copper mine in Australia, it was concluded that the SAB process offers the best combination of various factors such as total costs, operating costs, ease of management, and the possibility of future capacity expansion [11].

According to the major global grinding mill suppliers (Metso, FLSmidth, Thyssencrupp, Citic Hic, and Outotec), the choice of technology is most influenced by suitability for grinding duty, ore characteristics, and the range of available mill sizes. Equipment with a higher unit capacity, such as the SAG mill, is suitable for processing low-quality ore at high volume. The dominance of SAG mills and ball mills on the market in recent times is clear, although other grinding technologies are still relevant in mineral processing [4,15]. For example, the mineral processing plant of the Wushan copper mine, in China, has a production capacity of 30,000 t/d, which is divided into two identical production lines of 15,000 t/d each. This plant achieves the largest grinding capacity in China using the Φ8.8 × 4.8 m SAG mill [12].

In the countries of South America (Chile, Peru, Bolivia, and Argentina) according to data from 2014, a total of 42 semi-autogenous mills were installed and with over 30 projects taking into account the choice of the SAB process [13].

APPLICATION OF THE SAG CIRCUITS IN SERBIA

In recent years, copper mines in Serbia also followed a trend of moving from conventional to more innovative crushing and grinding processes.

Čukaru Peki copper and gold deposit belongs to the group of rich deposits and is located in the central part of Eastern Serbia, on the territory of the city of Bor.

In the grinding plant (Figure 8), a SAB process of two-stage grinding (semi-autogenous mill and ball mill) and one-stage classification of ground ore (hydrocyclone battery) is adopted (Figure 7).

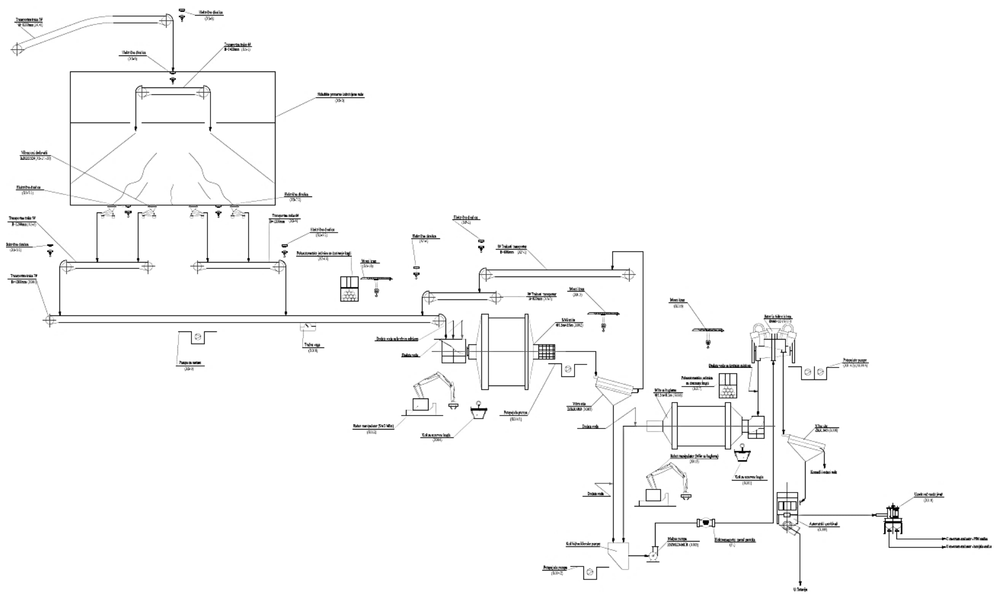

Figure 7, Technological scheme of the grinding process in Čukaru Peki grinding plant

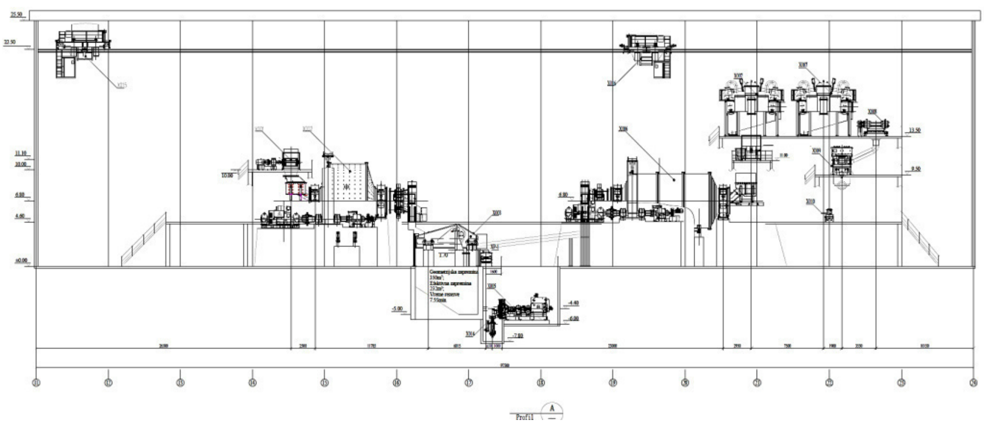

Figure 8, Cross-sectional view of Čukaru Peki grinding plant

Čukaru Peki grinding plant SAG mill characteristics:

- Inner diameter of mill (without liners) $D =$ 7,50 m
- Liners width $h =$ 0,26 m
- Inner diameter of mill (with liners) $D_S =$ 6,98 m
- Mill length $L =$ 3,90 m
- Max. ball diameter $d_k =$ 125,00 mm
- Mill charge coefficient $\varphi =$ 15,00 %
- Bulk density of grinding balls $\beta_k =$ 4,65 t/m^3
- Mill rotational speed $n =$ 12,30 o/min
- Critical rotational speed of the mill $n_k =$ 16,011 o/min

- Relative rotational speed of the mill $\psi =$ 76,82 %
- Installed engine power Ni = 4200,00 kW

Veliki Krivelj copper mine is located in the central part of Eastern Serbia, on the territory of the city of Bor, about 3km northeast of the city.

A new plant for mineral processing was built in 2021 with production capacity of 13,2 Mt/annually (Figure 10). Based on extensive considerations, the SABC process was adopted as final when selecting the grinding technology (Figure 9).

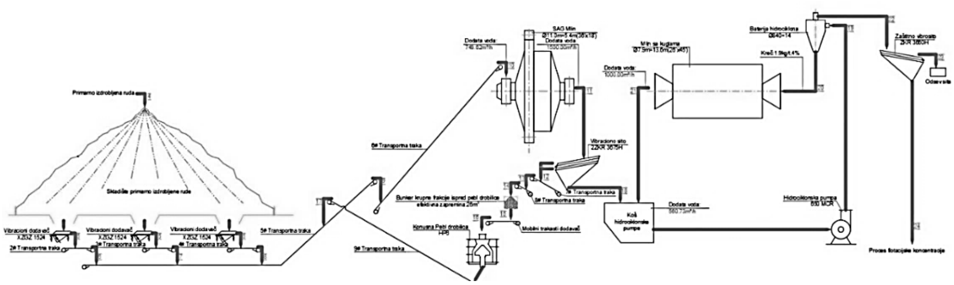

Figure 9, Technological scheme of the grinding process in the new Veliki Krivelj grinding plant

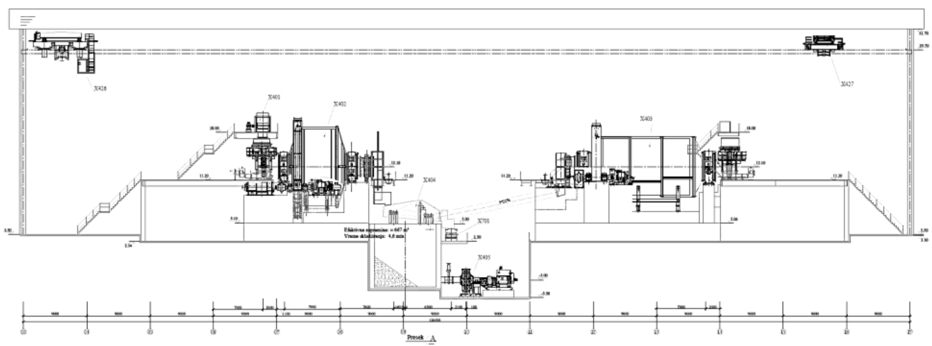

Figure 10, Cross-sectional view of the new Veliki Krivelj grinding plant

Veliki Krivelj grinding plant SAG mill characteristics:

- Inner diameter of mill (without liners) D = 11,00 m
- Liners width h = 0,22 m
- Inner diameter of mill (with liners) $D_S =$ 10,56 m
- Mill length L = 5,40 m
- Max. ball diameter $d_k =$ 100,00 mm
- Mill charge coefficient $\varphi =$ 20,00 %
- Bulk density of grinding balls $\beta_k =$ 4,50 t/m^3
- Mill rotational speed n = 9,74 o/min
- Critical rotational speed of the mill $n_k =$ 13,017 o/min
- Relative rotational speed of the mill $\psi =$ 74,83%
- Installed engine power Ni = 13000,00 kW

For the additional copper recovery from the smelter slag, a mineral processing plant was built, located within the **Serbia Zijin Copper smelting complex**, on the territory of the city of Bor

Grinding and classification of smelter slag takes place in the new plant (Figure 12) in two stages of grinding, in a SAG mill and a ball mill, and in two stages of classification in the primary and secondary battery of the hydrocyclone (Figure 11).

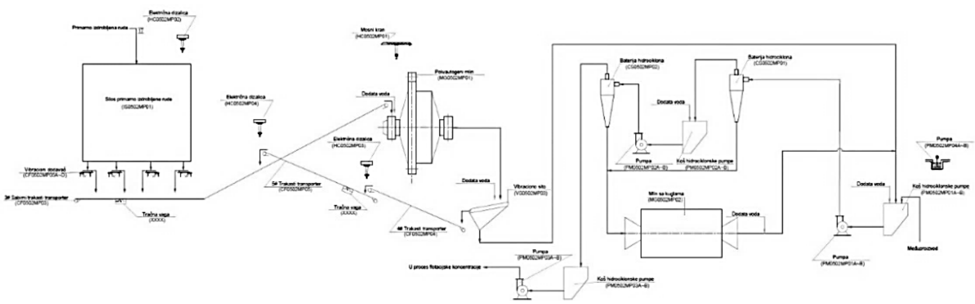

Figure 11, Technological scheme of the grinding process in the new smelter slag grinding plant

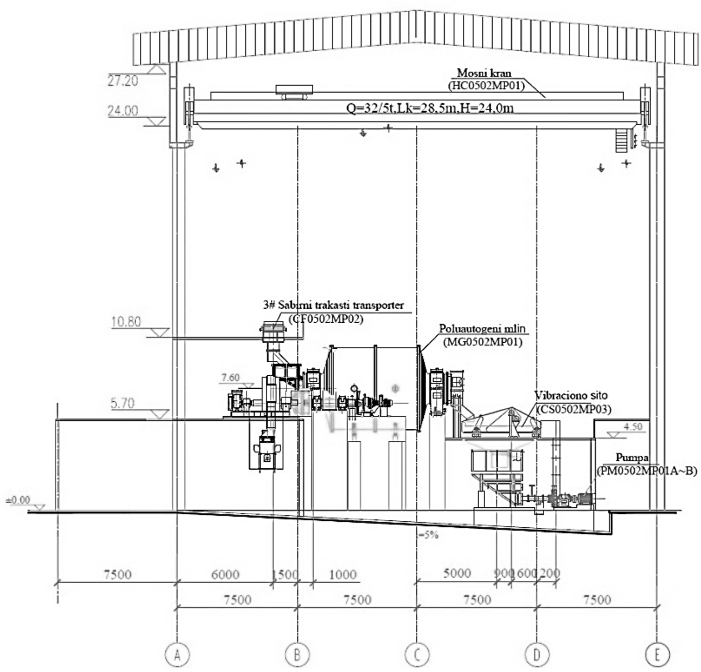

Figure 12, Cross-sectional view of the SAG mill in the smelter slag grinding plant

Smelter slag grinding plant SAG mill characteristics:

- Inner diameter of mill (without liners) D = 5,03 m
- Liners width h = 0,075 m

- Inner diameter of mill (with liners) D_S = 4,88 m
- Mill length L = 5,03 m
- Max. ball diameter d_k = 125,00 mm
- Mill charge coefficient φ = 14,00 %
- Bulk density of grinding balls β_k = 4,65 t/m^3
- Mill rotational speed n = 14,40 o/min
- Critical rotational speed of the mill n_k = 19,15 o/min
- Relative rotational speed of the mill . ψ = 75,20%
- Installed engine power Ni = 1800,00 kW

The location of the mineral processing plant for the ore from the **Majdanpek copper deposit** is in the southwest of the city of Majdanpek.

For the grinding technology in the new grinding plant (Figure 14), the SABC process was adopted, that is, one-stage crushing with two-stage grinding, where the first stage of grinding takes place in a semi-autogenous mill, and the second stage of grinding in a ball mill that works in a closed circuit with a hydrocyclone (Figure 13).

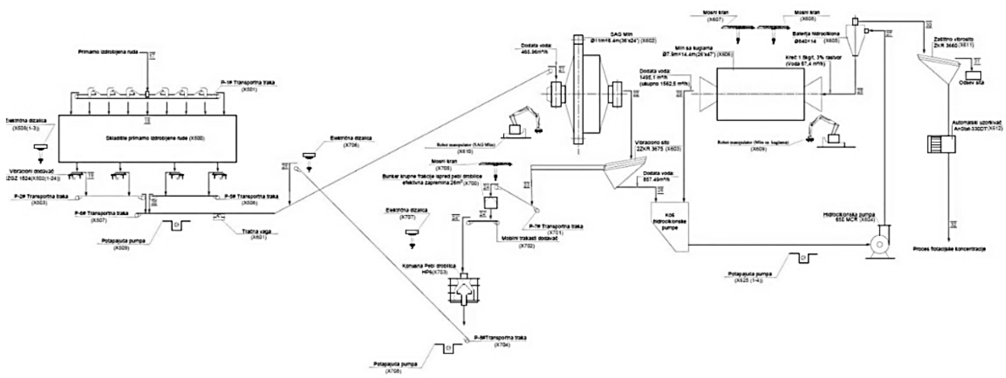

Figure 13, Technological scheme of the grinding process in the new Majdanpek mine grinding plant

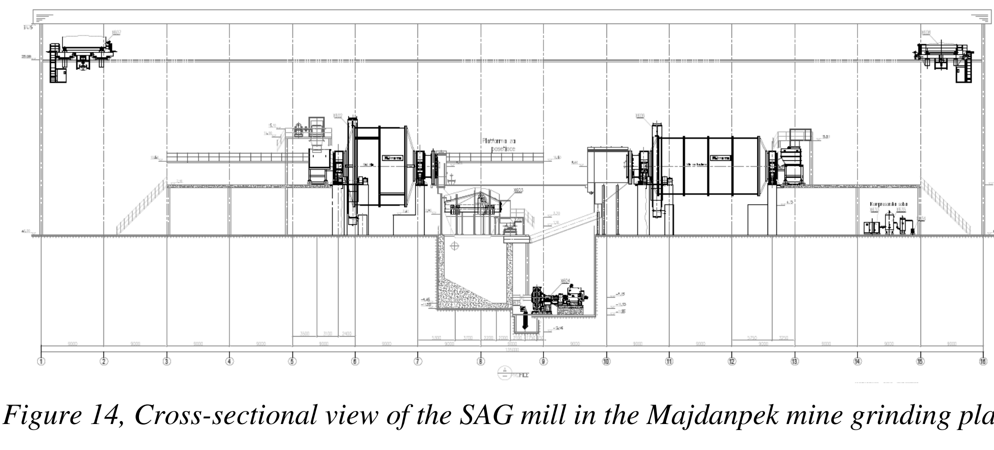

Figure 14, Cross-sectional view of the SAG mill in the Majdanpek mine grinding plant

Majdanpek mine grinding plant SAG mill characteristics:

- Inner diameter of mill (without liners) $D =$ 11,00 m
- Liners width $h =$ 0,325 m
- Inner diameter of mill (with liners) $D_S =$ 10,35 m
- Mill length $L =$ 7,30 m
- Max. ball diameter $d_k =$ 120,00 mm
- Mill charge coefficient $\varphi =$ 14,60 %
- Bulk density of grinding balls $n =$ 10,11 o/min
- Mill rotational speed $Ni =$ 17000,00 kW

CONCLUSION

Application of the SAG circuits is represented in large-capacity mines in many plants around the world. The advantages of this innovative process are reflected in its simplicity; it is a process that requires a smaller operating area, is characterized by a short construction period, the absence of dust due to the wet processing process, and a favorable working environment.

In the last 20 years or more, there has been a trend of moving from conventional to more innovative crushing and grinding processes.

The SAG circuits are more environmentally friendly, with less processing equipment, and more suitable for automatic control than the classic crushing and grinding methods.

The dominance of SAG mills and ball mills on the market in recent times is clear, although other grinding technologies are still relevant in mineral processing.

In recent years, copper and gold mines in Serbia also followed a trend of moving from conventional to more innovative crushing and grinding processes.

This paper presented the basic characteristics of a typical SAG mill, its application in grinding circuits, and in more detail gave emphasis on new technological schemes of grinding, and operating characteristics of SAG mills installed in Čukaru Peki, Veliki Krivelj and Majdanpek copper mines in eastern Serbia.

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