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FURNACE TAPPING

Advances in Robotic Tapping and Plugging of Non-Ferrous Smelting Furnaces: The MIRS Robotic Tapping Machine

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The operation of a metallurgical furnace requires the safe opening and closing of the furnace taphole. In this operation, the molten phase in the furnace is allowed to flow through the tap-hole for transfer to a ladle or another vessel before the tap-hole needs to be safely closed. Until now, non-ferrous tapping operations have largely been performed by an operator. Safe operations around the tap-hole require good process control of the smelting furnace, the proper tap-hole design for the required duty, and high-quality, robust tapping equipment. This paper briefly describes a new robotic tapping and plugging machine for the slag tapping operation on a large copper flash smelting furnace. The operating features and performance aspects are also summarized. Studies that indicate the applicability of this technology in operations other than slag tapping at a flash furnace are described.

INTRODUCTION

The metallurgical industry worldwide is in the process of transforming the way plants are designed and operated. Several changes have prompted this trend, including responses to climate change, global warming, cost reduction, and improved safety at plants. Other changes caused by advances in technology are higher computing power, connectivity and automation. Finally, the shift in metal demand and production from west to east is also a factor.

Furnace tapping and closing are critical steps in the operation of all pyrometallurgical processes involving molten phases—both the tap-hole design and operation are vitally important.

Today, virtually all non-ferrous pyrometallurgical furnaces rely on manually operated tapping machines—some remotely operated—for tap-hole opening and closing. Combining the high quality and performance of foundry model industrial robots and the technological skills of MIRS, the company has pioneered the successful development of a new robotic tapping and plugging machine. This paper describes the world's first industrial application of a robotic tapping machine for non-ferrous furnaces, including a summary of its performance for slag tapping at the Chuquicamata flash furnace in Chile.[1] Recent development work regarding furnace tapping operations carried out by MIRS on other types of metallurgical furnaces is also briefly described.

BRIEF REVIEW OF MIRS AND ROBOTIC TAPPING

MIRS, a Chilean company, dates back to the early 2000s and offers robotic equipment and technical solutions to the global mining industry. MIRS provides conceptual development, design engineering, manufacturing, integration, and support services for state-of-the-art robotic equipment and has developed numerous applications for mines, concentrators, tank houses, smelters and refineries. The applications are specially designed to withstand the harsh environments associated with heavy

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industrial operations, including acidic environments, extreme high temperature and high-altitude conditions, and severe vibration and dusty conditions. They also cover a broad range of industrial processes and are aimed at providing the following benefits:

- Increasing plant availability
- Lowering operating and maintenance costs
- Increasing process reliability
- Improving occupational health and safety aspects and reducing risks to personnel.

DESCRIPTION OF MIRS ROBOTIC TAPPING MACHINE AT CHUQUICAMATA

An agreement with Codelco was signed in the early 2000s to develop and install a robotic slag tapping machine at the Chuquicamata flash smelting furnace. The test work began in the laboratory followed by pilot testing before moving to test the unit at the smelter in 2007. Operational data regarding the flash furnace are presented in Table I.

Before the machine was installed, the manual operation required two operators on the tapping floor. The opening process used regular hollow oxygen lances and the closing used a clay plug that was affixed to the end of a steel bar. Both operators worked together under harsh conditions to open, close, sample, clean and measure the temperature.

A schematic sectional diagram of the tap-hole design in use at the time is shown in Fig. 1.

MIRS ROBOTIC TAPPING MACHINE

The robotic tapping machine was developed over the period 2002 to 2007 when commercial trials commenced. The machine remained in operation for 5 years until 2011 when large-scale smelter modernization work was carried out. The robotic tapping and plugging machine was later updated starting in 2018, with the robotic operation resuming testing at Chuquicamata in 2021.[2]

Including the upgrades made between 2018–2021, the robotic tapping machine consists of the following key features:

Robot

The heart of the machine is the robot unit. A KUKA KR 210 R2700-2 F machine was employed (Fig. 2). This robot has a payload capacity of 210 kg and a reach of 2.7 m. In operation at the flash furnace, the robot was covered with a heat protective robo-suit consisting of an aluminized Kevlar exterior and a Nomex interior. At the end of the

Table I. 2007 Operational data from the outokumpu flash furnace at Chuquicamata[1]

Item	Details
Tapping method	Manual lancing with hollow 14 mm outer diameter lance and occasional 25 mm solid bar, no machine
Plugging method	Manual with clay cone, no machine
Cu Conc feed rate	Up to 3,000 tpd (nominal)
Slag	1,220–1,575 tpd
Furnace shift schedule	Three 8-h shifts
Slag tap temperature	1250–1330°C
Length of tap-hole[a]	700 mm
Number of slag tap-holes available	4, each one ~ 150 mm in diameter
Approximate slag tonnage/tap	30–40 tons
Approximate number of slag taps/day	35–45
Opening time for slag tap-hole	~ 10 min for the first tap of a shift, ~ 1 min for successive taps during shift

2007 Typical flash furnace slag composition

Component	Assay range, wt%
Cu	1.5–2.5%
Fe	37.5–45.5%
Fe3O4	10.0–25.0%
Zn	1.0–5.0%
S	0.5–1.5%
SiO2	28.0–35.0%
CaO	0.8–2.0%

[a] The horizontal length from the faceplate to the inside of the wall of the furnace, refer to Fig. 1.

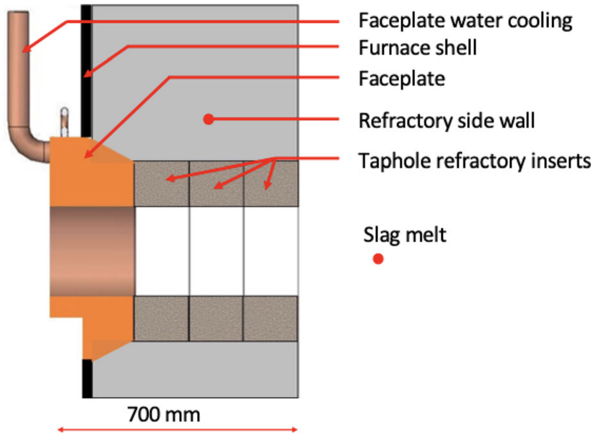

Fig. 1. Schematic diagram of taphole.

Fig. 2. KUKA KR 210 R2700-2 F Robot (Robo suit not shown).

robot's arm, included are the following: pneumatic grippers, force sensors and safety valves to allow picking up the exchangeable tools (mud gun, jack hammer and sampling) and for manipulating the disposable lances.

Lance

The lance, referred to as a "trefilated" lance due to the design of the internals, consisted of a 21-mm outer diameter steel pipe with an internal, steel star-shaped cross section to provide a more uniform and efficient oxygen flame.[3] This allowed a clean tap-hole opening with superior performance. The lance length selected, based on the selected robot, was 3 m. The operational oxygen pressure range is 5–10 bar (remains constant during operation), and the flow is 160–205 Nm^3/h; the optimal results are obtained at 178 Nm^3/h. The change from manual operation (hollow lance) to robotic (trefilated lance) plus the robot's capability of maintaining a straight line may reduce taphole wear and extend its lifetime.

Mud Gun

Plugging tool that consists of a hydraulic cylinder which injects clay into the taphole. It is designed to only inject a small amount of clay, enough to stop the flow. This allows an easier opening between taps. At the end of the shift, when operations move to a new taphole, more clay is added to the taphole to ensure it remains closed for the next 8 h and that this specific taphole will not be used during the new shift. The high forces are absorbed by a support that is latched to a bar affixed to the upper part of the taphole faceplate. The operator must load the clay gun from the outside of the fenced area by opening a small window that gives access to the front of the tool; sensors on this section indicate that the tool is not available until the fence is closed.

Jack Hammer

Electric hammering machine that the robot can use as needed. Its main function is to remove the solid clay plug after the taphole has been idle for > 1 h, exposing the hardened slag so that the lance tool can open. It is also used to open completely when the taphole has been plugged recently. A damping mechanism was included to avoid excessive, alternating high loads on the robot. This tool remains on a tool support table and the robot takes it whenever needed. This also allows it to be easily replaced or taken to the shop for maintenance.

Sampling Tool

The robotic sampler consists of a steel bar having a flat plate affixed at the end for collecting/retaining a suitable slag sample. This is similar to the sample bar used manually.

DESCRIPTION OF OPERATION

The following is a summary of the robotic tapping and plugging steps.

The robot unit is located inside a fenced area with the operator outside, away from the slag tapping zone. The operator initiates the robot's activities using what is referred to as the Human–Machine Interface (HMI). An automatic, pre-programmed operational sequence is then followed. The robot's movements essentially mimic the manual steps; the lance speed and oxygen flow are controlled depending on the resistance offered by the solid slag (utilizing force control) in such a way that if there is no resistance, the robot will speed up moving the lance until resistance increases. If resistance is high, the lance will slow down, make a circular motion or back up a short distance before continuing. The operator indicates when slag starts to flow whereupon the robot automatically withdraws the lance and places it in the lance holder. With the slag flowing, the robot then picks up the sampling tool

Fig. 3. Robot tapping with lance.

Fig. 4. Positioning the mud gun.

and, by pre-programmed movements, takes a slag sample and then deposits it in the sample bucket (Fig. 3).

When the slag in the ladle is at an appropriate level as determined by the operator, it activates the plugging sequence through the HMI and the robot automatically moves the mud-gun to the taphole (Fig. 4) and activates the clay extrusion mechanism to firmly close the slag taphole.

OPERATIONAL RESULTS

The on-line availability of the robotic tapping machine was $\sim$ 96% during the time when MIRS was carrying out measurements (this was for 256 8-h shifts).[1] The benefits realized from robotic tapping operations included:

- Increased plant availability—the more accurate lancing achieved with the robot increases the faceplate life cycle while reducing maintenance frequency.
- Increased process reliability—the robotic system always carries out the operations in the same way, leading to improved performance and better maintenance planning.
- Improved occupational health and safety aspects and reduced risks to personnel—the robot operator worked from the HMI located outside of the fenced area and, as needed, only accessed the area when the robot was locked out and when there was no molten material flowing.
- Lower operating cost—the manpower required to operate the robotic system is less than that for the manual operation. This also allows personnel to focus on tasks having a higher impact on the operation instead of repetitive manual labor.

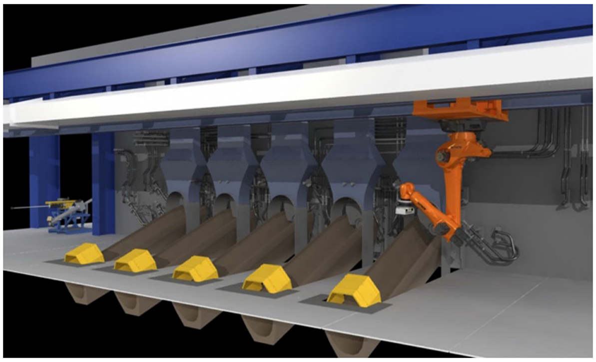

Fig. 5. Ceiling-mounted robot with linear rail.

The robot tapping machine was re-installed on the flash furnace in January 2021. Even though some remedial plant work was still underway, it was considered that tapping would not be affected. Shortly thereafter, Covid-19 pandemic conditions worsened, and, at the same time, with irregular furnace operations, a large hearth build-up of solidified material occurred in the slag tapping section of the furnace, severely affecting all operations including tapping operations because it required, amongst other aspects, lancing with much longer lances than the particular robot could handle. To carry out remedial work to correct this, the robotic tapping machine had to be removed to provide the necessary space. Codelco thanked MIRS for all efforts and reiterated that the removal of the machine was entirely because of the above smelter operational conditions and not at all related the robotic system.

STUDIES FOR POTENTIAL APPLICATION

MIRS has carried out a range of development studies on a number of different furnaces and tap hole configurations. Some of these developments are summarized below.

Ceiling-Mounted Robot

Many furnaces have multiple tapholes aligned on its sidewall or endwall. Given this, it is desirable to have a robotic machine that can easily move laterally from one taphole to another as required. In this

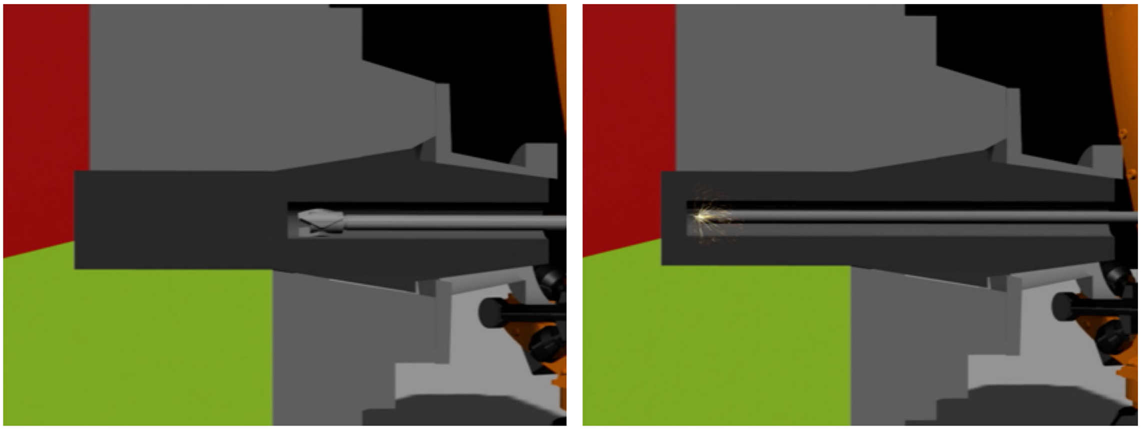

Fig. 6. Left, drill component. Right, lance component.

case, a ceiling-mounted system was designed; see Fig. 5.

Steel EAF Furnaces

The same technology described above for copper smelting has been applied at an engineering level to a tilting EAF used in the steel industry. One change however is to use a granular sand material for taphole closing. In the case evaluated, the taphole is plugged with the sand material after the furnace has tilted.

Drill Tool and Strategy for Copper Matte and Blister

A drill tool and related taphole strategy have been designed and tested under pilot-scale conditions. The drill is powered by an electric servomotor that allows the unit to control and monitor the drill speed, torque and pushing force. The strategy consists of drilling the clay plug and part of the clay/metal interface until a large increase in the controlled forces is met as shown in Fig. 6 left. At this point, the drill is withdrawn, and the robot continues with the lance until the taphole is opened Fig. 6 right. This strategy considerably reduces the chance of the drill being jammed in the taphole, which can be a common occurrence and can cause delays in the operation. The use of the lance is quite minimal, and the initial opening plus the lance guide on the exterior guarantees that the last section will be straight to protect the taphole walls.

Designs for Other Furnace Configurations

A robotic tapping machine has been designed for use on the furnace endplate such as on the El Teniente Converter or another similar type of operation; see Fig. 7.

Fig. 7. Design for use on a furnace endplate.

CONCLUSION

Robotic-operated slag tapping at a copper flash smelting furnace has been successfully demonstrated over an extended period of time as discussed in this paper. The unit comfortably handled the adverse operating conditions within its design, provided very reliable furnace taphole procedures and showed that a safer approach to furnace tapping is achievable. Removing personnel from high-risk areas is part of plant safety initiatives and overall ESG management at all mining and metallurgical operations world-wide. Improving safety around high-temperature furnace tapping therefore remains important. MIRS offers improved safety consistent with good tapping operations. Studies carried out show the applicability of this technology to operations other than slag tapping at a flash furnace. This includes EAF operations and other non-ferrous furnaces as briefly discussed in the paper.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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