Review of Technologies and Methods for Mold Powder Thickness Control

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The crucial role of mold powders in improving the quality of the cast products through proper mold lubrication and homogeneous heat transfer is well-established. Despite these crucial benefits, mold powders are typically fed manually, causing a variable powder thickness and steel meniscus instability, which in turn have negative effects on surface quality. In order to overcome these major criticalities, dedicated technologies enabling reliable mold powder thickness control and stable powder feeding are therefore needed. The aim of this paper is to give an overview of the main technologies and methods for mold powder thickness control and automated powder feeding technology, which enable to attain a reproducible casting process and an improved and constant quality of the cast products. The advantages of a new ultrasonic meniscus level sensor over traditional inductive devices are reported. A new powder diffuser with a novel built-in optical sensor is presented and the successful results of field-testing are commented.

KEYWORDS: MOLD POWDER FEEDING - POWDER THICKNESS CONTROL - OPTICAL SENSOR - LASER - ULTRASONIC SENSOR

INTRODUCTION

Mold powders play a key role in improving the quality of the cast products, while introducing significant benefits at both the metallurgical and process level [1-11]. As a result of powder feeding, a complex layered structure is produced in the mold, characterized by a multi-phase stratification in both the horizontal and vertical directions [1] (Fig. 1).

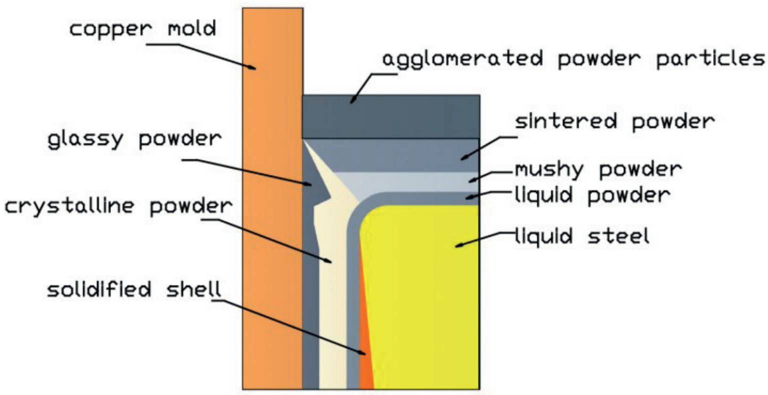

Fig. 1 - Scheme of multi-phase mold powder stratification [2]

As the solid powder is added on top of the mold, the powder melts generating a liquid slag pool. Due to the vertical temperature gradient and corresponding temperature decrease, a mushy and a sintered powder layers form on top of the liquid pool, while the in the topmost region the agglomerated powder particles remain at the solid state. Partial infiltration of the liquid slag into the mold-strand gap generates a thin, vertical film of liquid slag. As slag infiltration starts, the liquid slag partially freezes against the water-cooled mold wall, generating a glassy layer, which then partially crystallizes in the high-temperature region adjacent to the metal bath. Each powder layer plays a specific function, introducing key benefits [1]. The agglomerated and sintered layers protect the steel meniscus from oxidation and provide thermal insulation, preventing solidification of the steel surface and 'bridging' in the sintered powder layer. The liquid slag layer absorbs non-metallic oxide inclusions (mainly Al_2O_3

and TiO_2). The liquid slag film, combined with mold oscillation, provides mold lubrication. The vertical layers of solid slag drive horizontal heat transfer, which is recognized to be the controlling factor in longitudinal cracking [4-7,9], addressing the homogeneous growth of the solid shell and contributing to lower the breakout risk [1].

The quality of continuously cast products is greatly influenced by the fluid flow in the mold, particularly at the meniscus [12]. In order to minimize inclusion entrapment, it is especially important to keep nearly constant the liquid steel level in the mold and the powder feeding rate [13].

The thickness of the solid powder can be identified as the key variable to enable optimal powder feeding, based on the following considerations. Optimal mold lubrication is driven by the depth of the liquid slag pool, which is responsible for liquid slag infiltration in the mold-strand gap [1]. A constant thickness of the liquid slag layer is attained through a constant powder feeding rate [12], since under stationary conditions both the solid and liquid powder thicknesses are constant. Consequently, the reliable measurement of the solid powder thickness, while keeping it constant by closed-loop automated feeding, is sufficient to maintain also a constant depth of the liquid slag layer, getting this way stable conditions for proper solidification process as a guarantee for cast quality.

DRAWBACKS OF MANUAL POWDER FEEDING

Despite the key benefits described above, mold powders are typically fed manually by the operators, based on their subjective process experience. Being intrinsically unstable and poorly reproducible, manual feeding unavoidably leads to significant powder thickness variations. Since the radioactive steel level sensor measures a mass-weighted average of steel and powder, powder thickness variations translate into steel meniscus instability [16]. More specifically, each time powder is added manually, the radioactive sensor sees the powder thickness increase as a non-physical increase in the steel level. Since the density ratio of powder and steel is typically 1/3, a powder increase of 3 mm is seen by the radioactive sensor as a non-physical increase of 1 mm in the steel level. After each manual addition, the feedback signal of the radioactive sensor therefore causes an abrupt decrease in the physical steel level in order to keep the radioactive counts constant. As the powder progressively consumes, the powder thickness decreases and therefore the initial value of the physical steel level is gradually restored. This is a well-known phenomenon which has been extensively studied by dedicated modeling of the gamma rays attenuation through steel and powder [17]. As a conclusion, manual feeding unavoidably causes fluctuations of the steel level, which have a negative impact on the quality of the cast products [18].

TRADITIONAL POWDER THICKNESS CONTROL

In order to fully enable the key quality benefits associated with mold powders and to attain reproducible casting conditions, dedicated systems for mold powder thickness control and steel level monitoring are required. Steel level control through thermocouples embedded in the mold is not feasible for industrial process control since it implies very invasive mold machining. Innovative technologies were developed to enhance meniscus stability through optimized control over powder feeding [16]. A closed-loop mold powder thickness control was developed, consisting of an automatic powder feeder driven by the feedback signal from a radioactive sensor, measuring the mass-weighted average level of steel and powder, and an inductive sensor, sensitive to steel level only, installed within the water jacket [16] (Fig. 2).

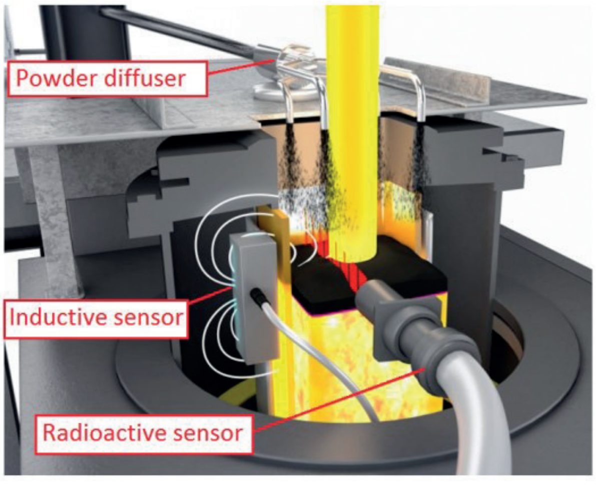

Fig. 2 - Representation of the inductive closed-loop powder thickness control system [2].

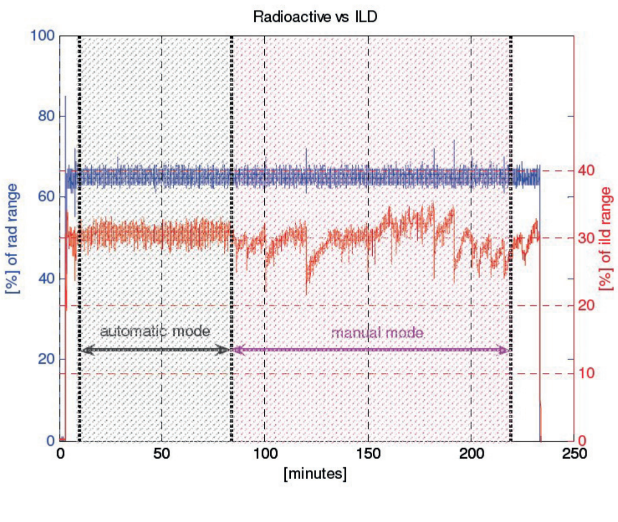

Fig. 3 - Industrial data: Performance comparison of automatic (left) and manual feeding (right) [16].

By combining the signals from the two sensors it is therefore possible to monitor variations in the powder thickness. This information is then used to provide a feedback signal to drive the automated powder feeding machine, keeping the powder thickness constant over time. The advantages of this technology in providing a stable meniscus level and a constant powder thickness have been extensively demonstrated by field-testing (Fig. 3). However, inductive sensors display several limitations. These sensors induce eddy currents into the copper wall of the mold and measure the temperature-dependent resistivity variation of copper, which is correlated with the steel level. Inductive sensors measure the average copper temperature in the region in front of the sensor, thus providing an integral temperature measurement. In order to estimate the meniscus level from the measured average temperature, a dedicated calibration procedure must be carried out at each casting start to determine the sensor response expressed as percent range. If no calibration takes place, the inductive sensor cannot determine the steel level. In addition, due to electromagnetic shielding by the copper mold wall (skin effect), inductive sensors are only sensitive to the temperature variation of the first 1-2 mm of copper on the external, cold side of the mold. This means the received electromagnetic signal does not include a contribution from the hot inner side of the mold, which is in direct contact with the liquid steel and is therefore more sensitive to sudden steel level variations.
As an alternative approach to inductive sensors, a multi-crystal radiometric sensor has been proposed for powder thickness and steel level monitoring [19]. The counts from multi-crystals are processed using a maximum likelihood algorithm able to discriminate the meniscus position and the thickness of the powder layer on top of it with a good level of precision on a time scale of a few seconds. The system has been tested on both small bloom and billet sections. Since it involves radioactive sources, this approach however features the same undesirable aspects associated with traditional single crystal radiometric mold level sensors, which require complex procedures for radioactive source handling and disposal, addressing operational and environmental safety.

ULTRASONIC SENSOR

In order to overcome the limitations of traditional inductive sensors, a new dedicated sensor based on ultrasound technology has been developed and field-tested [20, 21]. The sensor generates ultrasounds which propagate through the copper wall and are then received by an array of ultrasonic receivers. Since the ultrasound velocity in copper depends linearly on the copper temperature, dedicated processing algorithms enable to accurately extract the copper temperature at different positions along the mold wall. Therefore, the ultrasonic receivers act as an array of contactless "virtual thermocouples". The ultrasonic sensor is the first technology able to measure the meniscus thermal profile in real time through a fully contactless approach, exploiting a non-invasive installation within the water jacket. The steel level is then determined from the measured meniscus profile by dedicated processing algorithms, since a steel level variation corresponds to a translation of the meniscus profile (Fig. 4). This means that no calibration procedure is required, since the ultrasonic sensor is able to measure directly the steel level expressed as the distance in millimeters between the steel meniscus and the known position of the mold top.

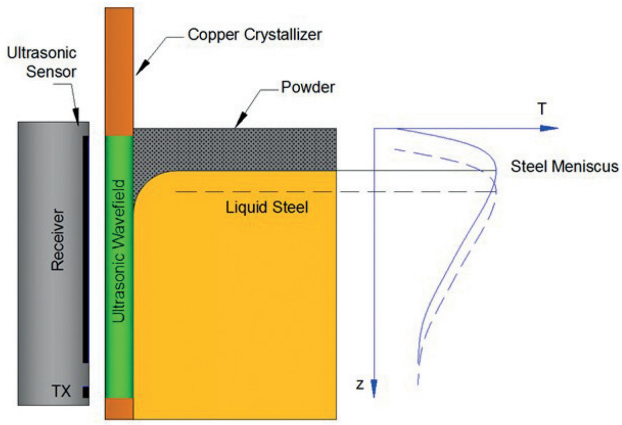

Fig. 4 - Installation layout and working principle of the ultrasonic sensor [20, 21].

This new technology provides both the steel level and spatially resolved thermal maps of mold temperature in the meniscus region, providing key information on casting conditions and solidification dynamics through an unprecedented contactless and non-invasive approach. The superior performance of the ultrasonic sensor over the inductive one has been demonstrated by comparative field testing, where synchronized data from an ultrasonic, an inductive and a radioactive sensor were acquired under different casting conditions [21]. Fig. 5 reports comparative industrial data at casting start:

1. Meniscus thermal profile measured with the ultrasonic sensor. The blue horizontal line is the radioactive level, while the superimposed red dashed line is the ultrasonic level;
2. Temperature measured with the ultrasonic sensors at different locations along the mold (locations are displayed as triangles of the corresponding colors on the right-side vertical axis of sub-graph 1.);
3. Comparison of ultrasonic (red) and radioactive (blue) absolute steel level in millimeters;
4. Comparison of inductive (green) and radioactive (blue) relative steel level expressed in percent range.

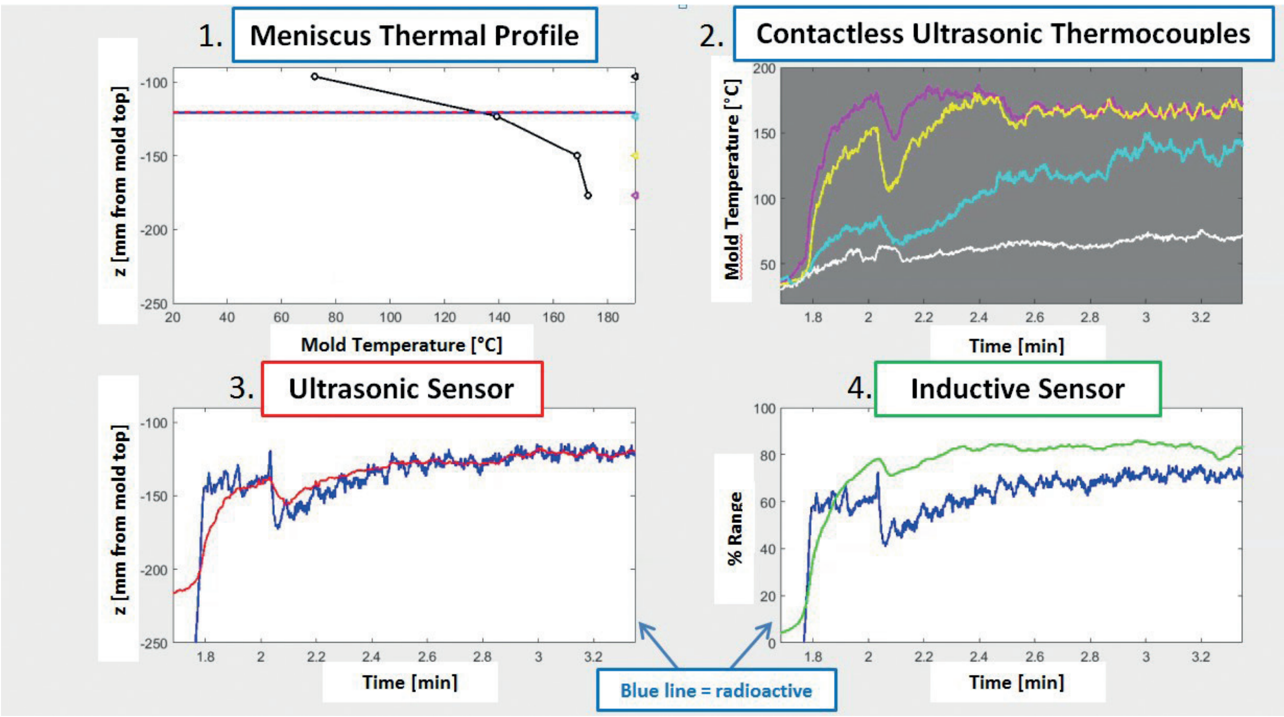

Fig. 5 - Results of comparative field-testing of ultrasonic, inductive and radioactive sensor (casting start) [21].

Based on the very positive results of field-testing, the ultrasonic technology is envisioned to fully replace the inductive sensor in closed-loop powder thickness control and powder feeding systems. The new implementation of the powder control system will therefore consist of the powder feeding machine, a pre-installed radioactive sensor and the new ultrasonic sensor, replacing the inductive one.

OPTICAL SENSOR

The optical sensor provides real-time measurements of the position of the powder surface. The sensor is based on the following working principle: A blue laser line is projected on the powder surface while images of the liquid bath are recorded by a camera (Fig.6). Real-time image processing based on dedicated triangulation algorithms enables to accurately monitor the position of the powder top surface with respect to the top of the mold.

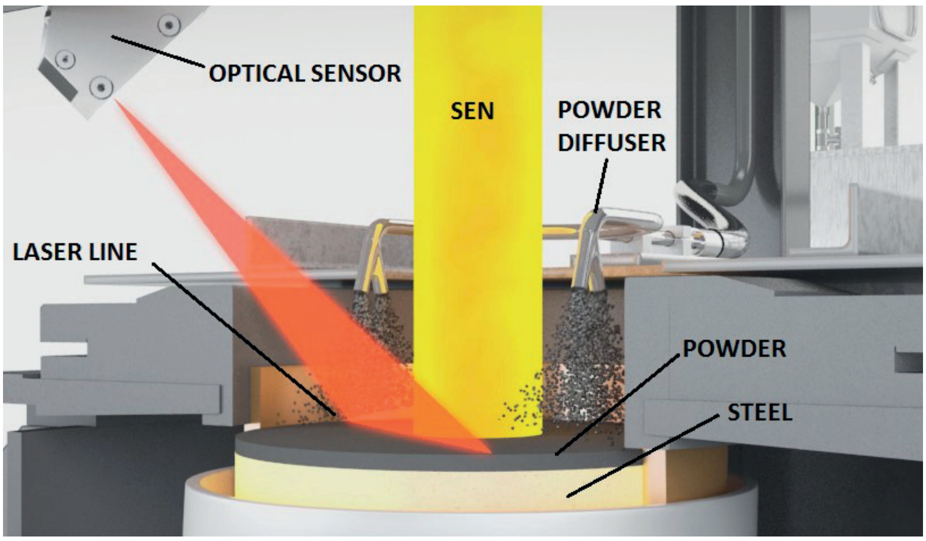

Fig. 6 - Layout and working principle of the optical sensor.

The optical sensor can be used to drive automated powder feeding in closed-loop configuration. In addition, by combining the information from the optical sensor with the data from a steel level sensor, it is also possible to determine in real time the instantaneous value of powder thickness. In this paper a further technological development is presented: a new miniaturized version of the optical sensor has been integrated directly into the powder diffuser, combining optical powder control with a compact, non-invasive installation. New powder diffuser instrumented with Optical Sensor

A new development of this technology enables to non-invasively install the optical sensor directly within the powder diffuser of an automated powder feeder: The powder diffuser arm is firmly secured to the top flange of the water jacket through a magnetic fast connector, the camera and the laser are integrated within a compact housing fixed to the arm, while a special mirror placed within the diffuser fork enables to deflect both the camera and the laser optical paths by 90° towards the liquid bath (Fig. 7, 8). In order to determine the powder thickness, both powder top and steel level must be measured. Therefore, the new optical sensor, sensitive to powder top, must be combined with either a radioactive sensor, affected by both powder and steel contributions, or with a thermal sensor (ultrasonic or inductive), able to detect the steel level without being affected by powder. In either case, the optical readings of the powder top level are then used as a feedback signal to drive an automated powder feeding machine in closed-loop mode.

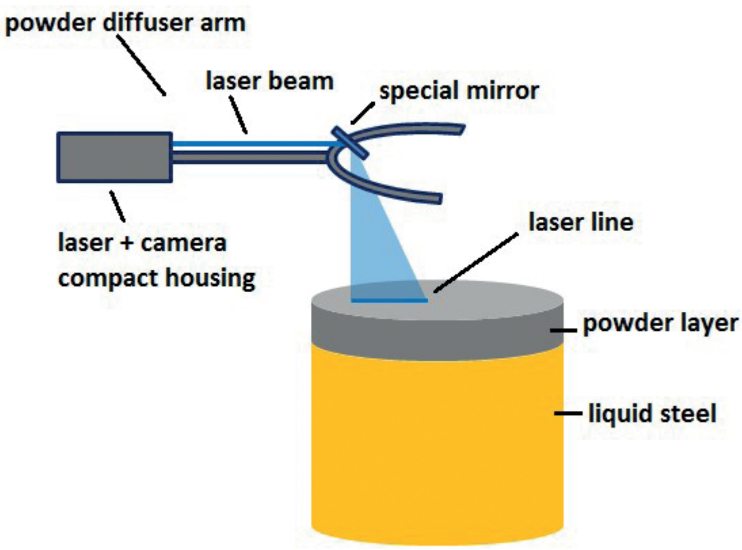

Fig. 7 - Powder diffuser with built-in optical sensor.

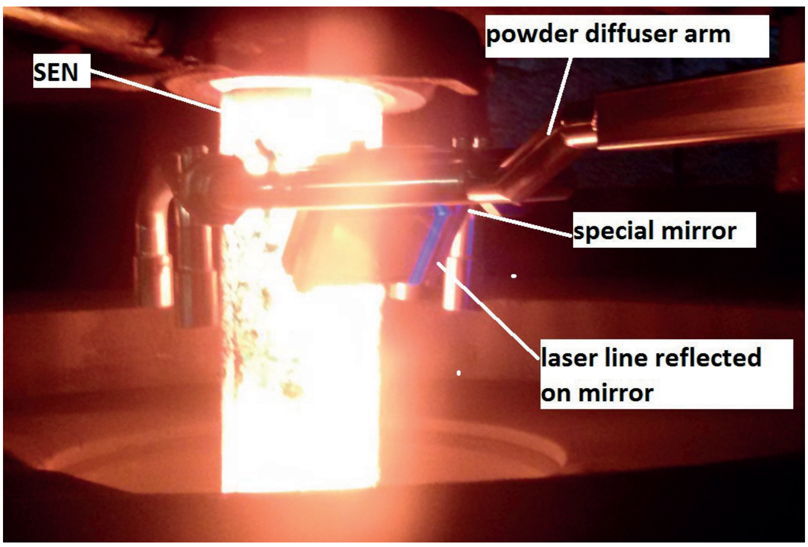

Fig. 8 - Installation of the instrumented powder diffuser.

The new powder diffuser arm with built-in optical sensor has been successively field-tested in a steelplant featuring a pre-installed radioactive sensor. The results of the industrial tests clearly demonstrate the superior performance of optical powder control with respect to manual feeding. Fig. 9 compares the powder top readings of the optical sensor when powder is added in manual mode (green and blue lines) as opposed to closed-loop mode (red line): Manual powder feeding gives rise to significant variations of powder top, which are strongly dependent on the subjective operator response. The green line shows a gradual powder consumption up to minute 14, when manual addition of a significant amount of powder is seen as an abrupt increase of the laser signal. The blue trend corresponds instead to a smoother, but still considerably unstable, operator intervention. Finally, the red graph demonstrates the superior performance of the closed-loop mode, where powder is continuously added by the automatic powder feeder driven by optical sensor feedback: the red line clearly displays a stable trend, characterized by low amplitude oscillations of powder top across a constant average value.

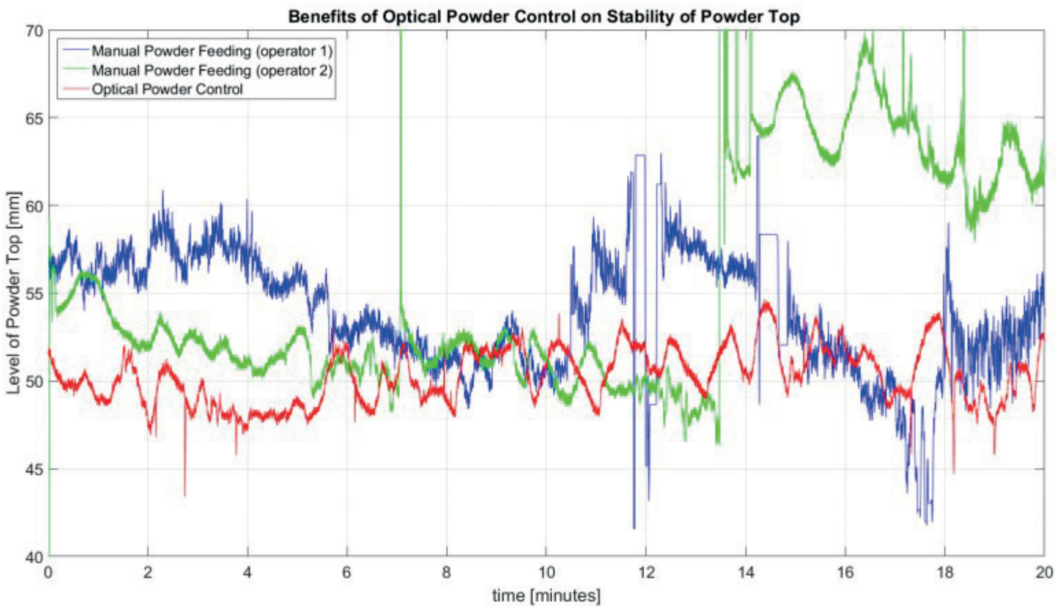

Fig. 9 - Optically measured powder top. Comparison of manual feeding (green and blue graphs) and closed-loop automated powder feeding based on optical feedback (red graph).

By keeping the level of powder top constant, optically-driven closed-loop powder feeding also ensures steel meniscus stability, which is known to have a key impact on surface quality [12]. In addition, closed-loop optical powder control enables to attain a constant powder thickness and in turn a stable mold lubrication, thus enabling a more homogeneous horizontal heat transfer and shell growth, translating to a more stable ΔT trend and improved mold friction, finally leading to improved surface quality.

APPLICATION RANGE OF ULTRASONIC AND OPTICAL SENSORS

In order to measure the powder thickness, both the powder top and the steel level need to be measured. This can be attained by a suitable combination of sensors, based on the casting format and on the sensors preinstalled in the casting machine. Even if the density ratio of steel and mold powder is typically 3, when large round formats are considered (ø > 300 mm), the response of the radioactive sensor to powder tends to be equivalent to its response to steel. In fact, for sufficiently large formats, the gamma rays attenuation by powder is so high to be indistinguishable from attenuation by steel within the statistical error. Under this condition, both the optical and the radioactive sensor measure the level of powder top. Based on these and similar considerations, Table 1 summarizes the application range of the optical and ultrasonic sensors, depending on the casting format and pre-installed sensors.

Tab. 1 - Application of the optical and ultrasonic sensors.

Casting format	Pre-installed radioactive	Pre-installed inductive (edge/suspended)	Suggested sensor
Billets	X		Ultrasonic or Optical
Small Blooms	X		Ultrasonic or Optical
		X	Optical
Large Blooms	X		Ultrasonic
		X	Optical
Slabs	X		Optical
		X	Optical

Advanced powder feeding and propulsion systems

Innovative propulsion systems for mold flux feeding were developed [2, 17], taking advantage of an innovative discrete pneumatic feeding through calibrated powder packets. By means of a special dosing valve and an air-powder mixer, a controlled volume of powder, the "powder packet", is dosed and pneumatically transported through the piping towards the diffuser arm. The powder flow rate is then fine-tuned by changing the shot frequency of powder packets, which is typically in the range of 10 shots per minute. Contrary to the other dosing and transport methods listed in Table 1, the packet technology enables to accurately control the dosed volume of powder and to fine-tune the powder flow rate. Since the velocity of the propelling gas is larger than the packet's one, during its path through the piping the packet undergoes a progressive spatial spreading. This phemonenon enables to keep a low air pressure at the diffuser outlet, thus causing no perturbation of the liquid bath surface. The powder feeding machine can work either in open-loop or closed-loop configuration. In open-loop, the powder flow rate is set manually by the operator and kept constant by the machine. In closed-loop, the flow rate (the frequency of the shots) is automatically controlled by the feedback signal from a pair of suitable sensors. The latter sensors pair may include a preinstalled radioactive sensor and a second sensor, sensitive either to the steel level (inductive or ultrasonic sensor, as previously described) or to powder top (optical sensor). Alternatively, the pair may include the optical sensor and an inductive sensor of edge or suspended type (Tab. 1). Table 2 compares the performance of traditional powder feeding methods with the benefits of the new powder packets technology.

Tab. 2 - Performance comparison of the main automatic powder feeding technologies.

Transport	Dosage	Simple	Economic	Fast Response	High transport distance	Uniform feeding through suitable diffuser	Low gas consumption	High accuracy	Good repeatability
Gravitational	Screw	X	X						
Screw	Screw			X					
Pneumatic, continuous	Screw				X	X			
Pneumatic, continuous	Pneumatic				X	X			
Pneumatic, discrete	Powder packets			X	X	X	X	X	X

CONCLUSIONS

Mold powders provide well-established quality and process benefits. Even so, mold powders are typically fed manually, with consequent lack of process reproducibility and a negative impact on steel quality. As a consequence, dedicated technologies are needed for mold powder thickness control and automated powder feeding. These include closed-loop powder control based on "powder packets", now taking advantage of new sensors based on ultrasound or laser-line technology. Ultrasonic technology enables to overcome the limits of traditional inductive sensors, providing a reliable and fully contactless measurements of the meniscus thermal profile and steel level, while keeping an advantageous installation within the water jacket. The level of powder top can instead be measured with a novel laser-based optical sensor, taking advantage of a new non-invasive installation within the powder diffuser arm. The reliability of optically-driven closed-loop powder control has been proven by field testing. Based on the casting format, a suitable combination of either the optical or the ultrasonic sensor with a preinstalled sensor (radioactive or edge/suspended inductive) enables to drive an automated powder feeding machine, implementing reliable closed-loop powder control and in turn leading to enhanced steel quality and improved reproducibility of the casting process.

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