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IFAC PapersOnLine 50-1 (2017) 438–445

A low-cost non-invasive slag detection system for continuous casting

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Abstract: The majority of steel produced today is made by the technology known in the steel making industry as continuous casting. Deciding when to stop the flow of molten steel from the ladle is not trivial, since terminating the process too early affects yield negatively, while closing the outflow valve too late lets slag enter the casting process. There is a variety of automatic slag detection systems available now, but numerous casting operations still rely on the decision of a human operator. In this paper, we propose a cost-effective non-invasive slag detection system that is based on the vibration signal measured during the casting procedure. In this method, the vibration acceleration data is analyzed by a cumulative sum (CUSUM) control chart in real time, providing a violation signal that can be used to close the ladle outflow valve. The proposed algorithm is implemented in an embedded microcontroller unit and is verified through a simulation study and laboratory experiments. These trials suggest that the technique may perform similarly to the human operator, however, just as in the case of the human operator, the disadvantage is that it only identifies the change when a small amount of slag already enters the tundish. Its advantage lies in its simplicity, low-cost, portable and non-invasive nature; possibly aiding the decision of the operator or, it may be used to create a completely automated ladle outflow valve closing system.

Keywords: vibration measurement, signal processing, time series analysis, steel industry, steel manufacture, statistical analysis, continuous casting, slag detection system, cumulative sum, ladle outflow

1. INTRODUCTION

The continuous casting of steel is a mature industrial technology accounting for a dominant part in global steel production. Surprisingly, there are several aspects of continuous casting that are not automated yet, relying heavily on manual labor and on empirical experience gained throughout its 150 year history instead (Thomas, 2001). Although control engineering technology and the means of automation have progressed immensely since the first continuous casters were made (Craig et al., 2001), numerous low-tech solutions that rely on heuristics are still in active use. The reasons for this are twofold. On one side, industrial practice is conservative and what has been working for decades tends not to be changed. On the other side, the casting shop is a very harsh environment for automation hardware; as most types of sensors and instrumentation are either useless or have a limited lifespan because of the high temperatures, dust, steam, electromagnetic radiation and occasional sprays of molten steel.

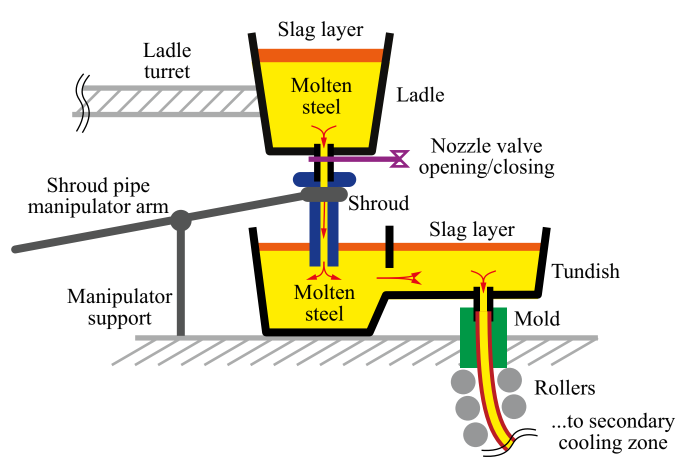

Fig. 1. Illustration of the continuous casting process.

In this paper, we take a look at one of those human-in-the-loop tasks that are still often employed in continuous

⋆ The authors would like to gratefully acknowledge the financial support granted by the Slovak Research and Development Agency (APVV) under the contracts APVV-14-0244, APVV-15-0201, APVV-14-0399 and APVV-0131-10. The authors appreciate the financial support provided by the Scientific Grant Agency (VEGA) of the Ministry of Education, Science, Research and Sport of the Slovak Republic under the contracts 1/0144/15 and 1/0317/17, and the Cultural and Educational Grant Agency (KEGA) under the contract 027STU-4/2017. The authors would also like to thank for the financial assistance from the STU Grant scheme for the Support of Excellent Teams of Young Researchers.

2405-8963
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.065

casting practice, and propose a signal processing method based on analysing vibration to make it more efficient, or to eventually replace it completely. Before we commence to introduce the specific problem, let us briefly review some essential aspects of the continuous casting technology.

1.1 Continuous casting technology

Continuous casting is based on the idea of using vertically oriented water-cooled copper moulds, into which molten steel is poured at the top, then continuously withdrawn at the bottom (Thomas, 2001; Hammerton, 1970). The initial phases of the process are illustrated in Fig. 1. Molten steel arrives at the on-cast position in a large *ladle* held by a rotating turret. The molten steel does not enter the mold directly; instead, it flows to an intermediate reservoir called the *tundish*. The role of the tundish is to act as a buffer in-between exchanging the empty ladle for a full one on the turret, to smooth out metal flow, to control flow into the mold, to distribute the metal between multiple casting strands and to leave time for impurities lighter than the metal to be discharged to the surface (Craig et al., 2001; Hammerton, 1970). Metal flows to the mold from the tundish where it is cooled enough to develop an outer solidified skin, then is withdrawn by rollers in a continuous fashion. The cast profile is further cooled by water–air nozzles in the secondary cooling zone, then finally cut into uniform lengths by a plasma torch (not shown in Fig. 1).

Molten steel reacts violently with oxygen in the surrounding atmosphere at temperatures up to $\sim 1600\ ^{\circ}$C; before it starts to cool down in the mold and the secondary cooling zone (see Fig. 2). This leads to oxidation, which must be prevented in order to make semi-products with the desired chemical composition and quality. Therefore, the molten metal is shielded from the environment by a layer of synthetic *slag*, floating on top of the molten metal in the ladle and the tundish. The slag layer serves as heat insulation as well. Similarly, the metal cannot just flow from the ladle into the tundish in open air; instead it is led through a submerged ceramic refractory *shroud* pipe (also called a *sheath tube*, see Fig. 2); which is usually inserted and removed by a simple manual manipulator arm. Besides shielding the metal flow from oxidation, the shroud is also important for safety reasons.

When the ladle is near-empty, the flow of the metal is shut off, the shroud pipe is removed and cleaned or exchanged if necessary; then the process repeats by re-inserting the shroud pipe under the full ladle, which is replaced by the rotating turret. The decision when to close the flow from the ladle is not trivial. If the flow of the metal is stopped too late, slag and other impurities may enter the tundish and the rest of the casting process. In extreme cases, slag may jam the nozzle and the casting process has to be started over. On the other hand, if flow is stopped too early, molten metal remains in the ladle and is essentially wasted, decreasing yield.

1.2 Slag detection systems

The problem of terminating the metal flow from the ladle is often referred to as slag detection. The first slag detection systems (SDS) utilized a pair of electromagnetic

Fig. 2. Molten metal reacting to atmospheric oxygen (right) when the shroud pipe (left) is removed. (Courtesy of ŽP Research and Development Centre.)

coils around the tundish (Julius, 1987), and this solution remains the most common as of today. Later ultrasonic, infrared and weight-based systems have also been proposed (Walker et al., 1991; Goldstein et al., 2000). These systems eventually evolved into commercial solutions, however, they require a steep initial investment, involve a complicated installation process that changes the caster and disturbs the casting process and necessitate frequent and expensive maintenance (Tan et al., 2010). Ultrasonic level meters and other standard industrial sensors—including electromagnetic sensors—are quickly worn out by the enormous temperatures in and around the ladle and shroud pipe.

Often, instead of the aforementioned commercial SDS solutions, the end of the casting process is simply decided by an operator securing and removing the shroud pipe by a manipulator arm (boom) (Fig. 3(a)). When the tensometers placed on the turret signal that only 5–10 tons of steel is left in the ladle, the operator simply grabs the shroud manipulator boom and "feels" for the exact moment when the flow should be shut off, as shown in Fig. 3(b). The decision is instantaneous and is followed by a voice command to an other employee to close the nozzle valve on the ladle. The shroud pipe is then quickly removed (Fig. 3(c)) to prevent the solidification of the metal inside and allow its possible re-use with the next ladle. The empty ladle is then moved to the off-cast position and exchanged with the new one using the turret, re-starting the procedure.

According to the comprehensive literature survey article on slag-detection by Tan et al. (2010), the value of this heuristic method was first recognized in the 1980's by Itoh et al. in a Japanese language article; suggesting the use of the vibration signal to create a SDS. Trotter et al. (1991) and others put forward the idea of using artificial neural networks (ANN) for processing the vibration signal. Li et al. (2005) proposed that the relevant information on the slag content of the ladle may be extracted by hidden Markov models (HMM) in combination with vector quantization (VQ) from the vibration signal, then further