Management practices to conduct ladle treatment processes in the steel industry: a systematic literature review

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Abstract: In an increasingly competitive context, the European steel industry has to introduce innovative solutions and focus on high-quality production. A key part of the steelmaking process able to increase the product quality is the secondary metallurgy undertaken in Ladle Furnaces (LFs), i.e. a refractory lined vessel, where steel reheating, alloying, and inclusion removal are performed. To increase the efficiency of this equipment, twin LF stations have been recently introduced. This technology also permits enhancing the quality performance, and reducing energy consumption, adverse environmental impacts, and risks for workers. Management practices can facilitate the achievement of such objectives, representing a low-cost lever for enhancing production systems. For these reasons, we carried out a systematic review in the scientific literature about the management practices that enable an effective conduction of ladle treatment processes in a twin LF and in a traditional LF configuration. Twenty practices are identified and analysed based on a set of factors properly defined for this study. The results show that there is only one practice specific for the twin LF management: this is based on the Case-Based Reasoning method to predict the end temperature of molten steel for improving both energy efficiency and quality level. Regarding a traditional LF, the majority of existing practices are focused on the attainment of product quality benefits and on proposals of models to monitor process parameters, optimise energy consumption, and obtain high-quality products. These results may stimulate companies in the implementation of management practices to effectively conduct ladle treatment processes.

Keywords: Productivity; Non-technical measure; Energy saving; Industry 4.0; Sustainability

1. Introduction

The steel industry represents a key sector for Europe’s economy and competitiveness, and plays an important role in the achievement of improved industrial energy and environmental performance (Stefana et al., 2019a, 2019b). To face the competition in the global market, steel companies have to focus on how to reduce cost and energy consumption, and produce high quality products satisfying various customer demands (Tian et al., 2017). In such a context, the secondary metallurgic process is very important to improve the quality of products (Tian et al., 2017). An effective method of secondary steel refining requires the use of Ladle Furnaces (LFs) (He et al., 2012), which is a refractory lined, cylindrical-shaped vessel (Mazumdar and Evans, 2010). LF is the equipment involved in treatment procedures of the steel production, where the generated molten steel is cast and heated by means of three graphite electrodes that are connected to an arc-transformer (Najm et al., 2021). The LF treatment includes steel reheating, alloying, deoxidation, desulphurization, and inclusion modification; the homogenisation, inclusion removal, and steel/slag reactions are favoured by the steel stirring through argon purging (You et al., 2020). Therefore, the purpose of LFs is to produce qualified steel grades and ensure the temperature of molten steel for continuous casting (Tian et al., 2017). In addition to the advantages in terms of quality and control, LF also allows keeping a thermal balance between the steel and ladle brick, and attaining high productivity level (He et al., 2012; Sampaio et al., 2007). Further descriptions and schematic representations of this equipment can be found in Mazumdar and Evans (2010), and Najm et al. (2021).

Recently, in order to increase the LF efficiency, twin LFs stations have been developed. A twin LF is a flexible solution composed of two stations and one set of electrode arms that can be swivelled to both stations, which allows heating of one ladle and simultaneously having the possibility for other ladle treatments (Redl et al., 2019; Spiess et al., 2005). Besides this versatility, such technology permits reducing the waiting times between the different stages of production, increasing the productivity level, enhancing the “clean steel practice”, and decreasing energy consumption, adverse environmental impacts, and health and safety risks for workers. Some examples of possible twin LFs are available in Redl et al. (2019).

To facilitate the achievement of the different objectives mentioned above, companies can adopt management practices. In accordance with Stefana et al. (2019a), a management practice is “a strategy for managing a plant’s operational activities in order to produce a desirable outcome". Management practices are attracting increasing interest from researchers and practitioners since they represent a valuable low-cost and non-technical means for enhancing production systems and operations (Stefana et al., 2019a). The adoption of such practices permits saving resources that could be used to finance subsequent investment in efficient technologies (Stefana et al., 2019a). For this reason, we carried out a systematic review in the scientific literature about the management practices that could enable an effective conduction of ladle treatment processes performed in a twin LF and in a traditional LF configuration. Given the similarities in terms of production processes and cycles, we analysed both twin and traditional LFs in order to capture as many results as possible. Our aim is to focus on practices leading to benefits in terms of improvements on energy efficiency, environmental performance, workers' safety, and product quality.

The remainder of the paper is organised as follows: Section 2 describes the methods followed in this research. Results are presented and discussed in Section 3, and concluding remarks are provided in the final section.

2. Methods

We performed our systematic review based on the Preferred Reported Item for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009). This permitted identifying and analysing all relevant studies answering our research question: "Which management practices could be adopted to improve energy efficiency, environmental performance, workers' health and safety, and/or quality level in ladle treatment processes in the steel industry?". This research question was framed in terms of the acronym CIMO that helps to structure the search string; in particular, the keywords of the research question are the following: (1) ladle treatment processes for C (Context); (2) energy efficiency, environmental performance, workers' health and safety, and/or quality level for I (Interventions); (3) none for M (Mechanisms) because not relevant for our purpose; (4) practices for O (Outcome).

The relevance of each retrieved paper was assessed according to the following inclusion criteria: (1) only papers written in English; (2) only papers proposing at least one practice for the improvement of energy, environmental, safety, and/or quality aspects; and (3) only studies concerning processes undertaken in ladle furnaces in steel companies. Besides these inclusion criteria, we defined some exclusion criteria for helping in the study selection of the papers: (1) papers proposing a practice not explicitly applicable for ladle furnace treatments; (2) studies describing practices for achieving benefits different from energetic, environmental, safety, and quality ones; and (3) papers dealing with a comparison of different existing technologies for secondary metallurgy. The literature search was conducted in the following electronic databases: Scopus, Web of Science, Wiley, Taylor & Francis, EBSCO, and Emerald Insight. We chose these electronic databases due to their pertinence to the research topic and scope. The searches were performed on 20 November 2019. Each database was queried from the date of the oldest indexed paper in order not to exclude potentially relevant studies. The search was limited to English documents. We employed the reference management software Endnote® X9 to record and manage references, to remove multiple records, and to create a unique database of references. A further step of manual removal of other duplicates allowed obtaining our initial database. In order to select the relevant studies, the papers within the database were screened by applying a three-stage process based on Stefana et al. (2015): (1) title evaluation, (2) abstract and keywords evaluation, and (3) full-text evaluation. In each screening stage, three reviewers critically appraised the papers independently; all the documents selected by at least one reviewer have been promoted to the successive screening stage to be over-inclusive and minimise the chance to discard relevant studies (Marciano et al., 2020). Finally, we collected the included studies (i.e. the documents answering the research question) in the final database. Such studies are characterised and analysed by means of some comparison dimensions defined ad hoc for our study. The entire selection process and results obtained in each stage are displayed in Figure 1.

3. Results and Discussion

This systematic literature review permitted retrieving a total of 20 studies, each one proposing a different practice to improve energy efficiency, environmental performance, workers' health and safety, and/or quality level in ladle treatment processes in the steel industry. To analyse these studies, we defined a set of factors: (1) brief description of the practice; (2) type of practice, e.g. if the practice is a mathematical model or deals with the recycling of used materials; (3) type of LF, i.e. twin LF or traditional LF; (4) potential of improvements in terms of energetic, environmental, safety, and/or quality aspects; (5) possible economic savings for steel companies deriving from the application of the practice. Table 1 reports the results of the 20 studies (in alphabetical order by author) with respect to such factors.

3.1 Management practices and their types

Half of the studies propose practices based on the development and application of mathematical models characterised by different complexity levels. The proposed mathematical models are able to estimate key parameters in the steel ladle management, based on available inputs and variables, and mainly employing conservation equations describing the refinement process. Among them, four approaches are focused on the prediction of the temperature of molten steel in LF: He et al. (2012) propose a Case-Based Reasoning method, Sampaio et al. (2017) a neural network thermal model, Tian et al. (2009) a hybrid modelling based on the combination of a thermal model and an intelligent one, and Tian et al. (2017) an operation optimisation method based on AdaBoostIR soft sensor.

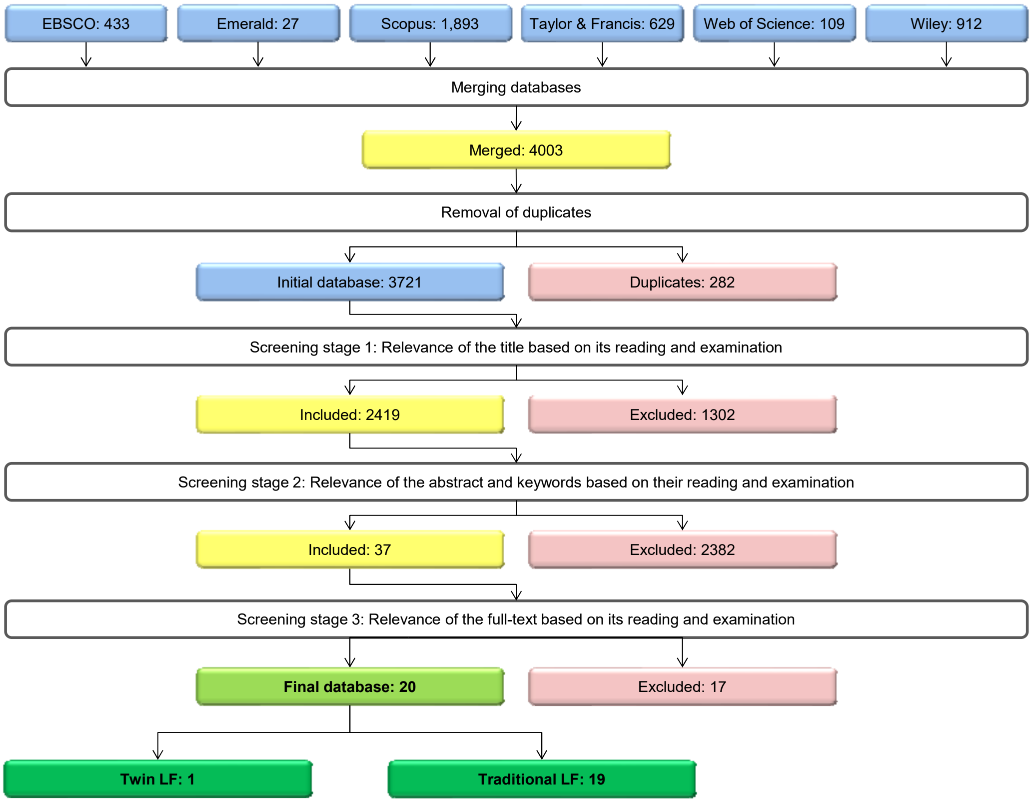

Figure 1: Summary review flow diagram

The remaining 6 models allow determining other key parameters in the steel ladle management: e.g. the optimised quantity of ferroalloys for obtaining the desired steel chemistry (Kothari et al., 2017), or the design set points of ladle operation to meet the desired properties of a cast slab (Shukla et al., 2015).

Five studies describe practices for the reuse of ladle furnace slags internally or externally. Their external reuse is the most quoted application: e.g. hot asphalt mixtures (Bocci, 2018), mortars (Borges Marinho et al., 2017), or soil stabilisation (Ortega- López et al., 2014). All of these five studies highlight the environmental benefits achievable by the application of the practices. The only study proposing an internal slag reuse (Guzzon et al., 2007) mention further benefits, such as the improvement of energetic and safety performance, the attainment of economic savings, the reduction of the consumption of the refractory bricks of the Electric Arc Furnace (EAF) and of the powder dust present in the plant.

Two practices (da Cruz et al., 2016; Kaushik et al., 2019) focus on process parameter analysis: the authors conducted several campaigns and tested different process condition changes to experimentally analyse their effects on the product quality. The practice suggested by Kaushik et al. (2019) appears particularly interesting because its adoption could improve the overall steel cleanliness and customer satisfaction, increase the productivity level, and lead to economic savings. The remaining studies focus on different types of practices: e.g. Boenzi et al. (2019) perform a Life Cycle Assessment (LCA) to compare two systems of refractory types. This is the only study in the retrieved literature addressing the possibility to achieve all the four improvements under investigation.

3.2 LF types

Only one practice is defined for a twin LF configuration: He et al. (2012) develop and validate a model to predict and control the molten steel temperature. This study is based on the analysis of the LF refining process and energy equilibrium, and determines the main influence factors of end temperature of molten steel in LF, such as steel grade, ladle heat status, starting temperature of molten steel, refining time, and argon consumption. The adoption of such practice permits improving both energetic and quality performance.

The majority of the practices are designed for a traditional LF, probably because this equipment is largely employed in the steel industry and several studies focus on the continuous improvement of its management. On the contrary, the scarcity of practices devoted specifically to the twin LF is presumably linked to its novelty and limited diffusion. This calls for future researches able to define specific measures for this ladle furnace or to test the applicability of the existing practices for a traditional LF to a twin LF configuration.

3.3 Energetic, environmental, safety, quality benefits

Most of the practices (13 out of 20) are designed to achieve better quality performance by means of a specific mathematical model, a material analysis, an investigation of process parameters, or an addition of materials.

Table 1: Analysis of the 20 management practices in the reviewed literature

Study	Description (type of practice)	LF	Improvements				ECO
		type	ENE	ENV	SAF	QUA	
Bocci (2018)	Evaluation, definition of a procedure, and validation for reusing ladle furnace slag as filler in hot asphalt mixtures (reuse of by-products)	Tr		x			
Boenzi et al. (2019)	Life Cycle Assessment to compare two systems of refractory types considered, magnesia-carbon and magnesia-alumina (material analysis)	Tr	x	x	x	x	
Borges Marinho et al. (2017)	Development of a sustainable binder for mortars from ladle furnace slag as a substitution of hydraulic lime (reuse of by-products)	Tr		x			
da Cruz et al. (2016)	Analysis of operational variables and materials properties of the filler sand to increase free opening efficiency of ladle (process parameter analysis)	Tr			x	x	
Guzzon et al. (2007)	Recycling of the ladle slag withing EAF through the injection system (reuse of by-products)	Tr	x	x	x		x
He et al. (2012)	Case-Based Reasoning method to predict end temperature of molten steel in LF (model)	Tw	x			x	
Kaushik et al. (2019)	Establishing of steelmaking parameters to ensure sulfide shape control without undue MnS stringers and oxide inclusions (process parameter analysis)	Tr				x	x
Keshari et al. (2012)	Addition of calcined bauxite to the flux mix to modify slag properties and optimise slag composition and gas purging regime (addition of materials)	Tr	x		x	x	
Kothari et al. (2017)	Real-time ferroalloy model to predict an optimised quantity of ferroalloys required for achieving the desired steel chemistry (model)	Tr				x	x
Ortega-López et al. (2014)	Application of ladle furnace basic slag in soil stabilisation (reuse of by-products)	Tr		x			
Picon et al. (2018)	Regression algorithm to mathematically map the spectral reflectance of the slag with its actual composition (model)	Tr	x			x	x
Rodriguez et al. (2009)	Preparation of ladle furnace basic slag for the manufacture of masonry mortars for use in the construction industry (reuse of by-products)	Tr		x			
Sampaio et al. (2007)	Neural network thermal model to predict online steel temperature of the ladle furnace process (model)	Tr	x			x	x
Shukla et al. (2015)	Computational method to determine the design set points of ladle, tundish and casting operation to meet the desired properties of a cast slab, for a given input of molten steel to the ladle (model)	Tr				x	x
Tian et al. (2009)	Hybrid modelling for soft sensing of molten steel temperature in LF, based on the combination of a thermal model and an intelligent model (model)	Tr				x	
Tian et al. (2017)	Operation optimisation method of molten steel temperature based on AdaBoostIR soft sensor (model)	Tr	x			x	x
Viale et al. (2007)	Application of on-line infrared thermography to prevent a leakage of liquid steel due to heating process (installation of cameras)	Tr			x		x
Xia and Ahokainen (2003)	Numerical investigation of transient two-phase flow and heat transfer in a gas-stirred steelmaking ladle with gas injection (model)	Tr				x	
Yetisken et al. (2013)	Cost and exergy analysis for optimisation of charging materials by means of linear programming and considering EAF and LF as a system (model)	Tr	x			x	x
Zhang et al. (2009)	Mathematical model for gas flow and heat transfer in LF lid based on 3-D Navier–Stokes equations, k–e two equation turbulent models, and energy conservation equation (model)	Tr	x	x			x

Abbreviations: Tw = Twin LF; Tr = Traditional LF; ENE = energy; ENV = environment; SAF = safety; QUA = quality; ECO = economic savings.

In addition to quality improvements, three of these studies (Kaushik et al., 2019; Sampaio et al., 2007; Yetisken et al., 2013) emphasise the possibility to also obtain economic savings and a productivity increase. This has been verified by means of application in real plants: ArcelorMittal Coatesville by Kaushik et al. (2019), V&M by Sampaio et al. (2007), and a plant located in Turkey by Yetisken et al. (2013). Sampaio et al. (2007) suggest that a standardisation of the number of measurements to one for every ten minutes of process halves the mean number of thermocouples used per heat, and saves around US$ 33,000.00 in 2930 heats (equivalent to a 4 month-production). In general, the practices retrieved through our systematic review have been largely applied in real case studies, but not always the articles provide a complete description about such application. This could discourage steel managers from adopting the practices because of the scarcity of details related to the technical features of the plant and the estimation of the quantitative benefits. Therefore, future studies describing extensive practice utilisations are highly encouraged.

Nine practices have the purpose to obtain energy savings, mainly based on model definition, whereas seven studies are concentrated on environmental benefits primarily thanks to the recycling of by-products. In the study by Keshari et al. (2012), the modification of slag properties thanks to the addition of calcined bauxite to the flux mix leads to a fall in purging gas consumption of 30%, while Guzzon et al. (2007) highlight that the use of the recycling of ladle slag in European steel plants would reduce the utilisation of natural lime stones of about 30%. In this direction, Ortega-López et al. (2014) state that "the contribution of LFS [ladle furnace basic slag] use to global sustainability is enormous, substituting the consumption of large amounts of quicklime or cement and proportionally reducing atmospheric greenhouse gas emissions". Because the steel industry is highly material and energy intensive (Stefana et al., 2019a), increasing attention should be paid on energy efficiency and environmental performance.

Only a minority of studies (5 out of 20) concentrate on the achievement of better health and safety conditions for the workers. One of them (Viale et al., 2007) quotes safety improvements as the main benefit type linked to the application of their management practice. This study is related to the installation of cameras to prevent liquid steel leakages due to heating processes that allow providing alarms and improving the process knowledge. The shortage of safety practices highlights the need to further strengthen the attention on hazards and risks typically encounter in the steel industry and management actions for facing them. The definition of new practices focused on health, safety, and ergonomic aspects should also consider real-time data and periodical risk evaluations as a key improvement to allow for effective decision-making support (Bucelli et al., 2018).

3.4 Economic savings

Half of the studies explicitly mention the possibility to obtain economic savings as a result of adopting the practices. For instance, Kothari et al. (2017) report quantitative data about the savings achieved in the implementation of a ferroalloy model in three LFs in Tata Steel LD shop: the adoption of the practice permits reducing the average manganese from 0.76 to 0.74%, which is translated into 60-70 kg/heat reduction in ferroalloy consumption (assuming a 150 tonnes heat). Picon et al. (2018) describe the minimisation of the cost to reach the target steel quality with lower energy and additive costs that has been validated on several ArcelorMittal locations, achieving process savings of 0.71 € per liquid steel ton. Yetisken et al. (2013) propose a linear programming based on the cost function for EAF and LF systems based on the costs of the energy and materials in a Turkish steel company. Economic considerations represent one of the fundamental pillars in a Triple Bottom Line (TBL) approach to sustainability (Pope et al., 2004). According to Pope et al. (2004), "the TBL can be considered an interpretation of sustainability that places equal importance on environmental, social and economic considerations in decision-making". Also for this reason, the economic aspects of the adoption of the practices should be deeply investigated, also by means of structured approaches. With this regard, a Cost-Benefit Analysis (CBA) seems a promising tool to assist decision-makers through the translation of costs and benefits in a common currency, usually money, to enable the comparison of like quantities (Paltrinieri et al., 2012).

3.5 Requirements for practice implementation

A critical analysis of the retrieved practices points out the need of the involvement of staff with specialised and diversified competences. Indeed, some practices are advanced methods and analyses requiring a deep knowledge and expertise of the general steel production process and the refining treatments in LFs. For example, Sampaio et al. (2007) state that during the selection of the variables of their neural network model, the global knowledge of the process and the presence of specialists in secondary metallurgy are essential.

The proper application of some management practices originates from the familiarity with tools and software not commonly used in companies. For instance, Boenzi et al. (2019) employ the software program OpenLCA for carrying out the modelling and the Life Cycle Impact Assessment (LCIA) of two refractory brick product systems, while Zhang et al. (2009) use a grid-generation tool to create the computational zone, and generate the grids of LF lid system (GAMBIT 2.1.6 of Fluent Inc.) and a code for computational fluid dynamics for simulations (FLUENT 6.1). The practices concerning the reuse of by-products are based on the knowledge about the properties of ladle furnace slags and the evaluation of the ones that appear particularly promising for the manufacturing of other products. For example, Bocci (2018) deals with the physical and chemical properties of ladle furnace slags to verify the possibility to reuse it in hot bituminous mixtures, whereas Borges Marinho et al. (2017) assess the technical feasibility of a new sustainable binder for mortars, also considering Brazilian and Portuguese standards related to the hydrated and hydraulic lime.

A set of equipment able to collect data and monitor real-time behaviour of the systems represents a fundamental element for assuring an effective practice adoption. Picon et al. (2018) provide details about the acquisition system for estimating real-time slag composition and acquiring different process data in order to monitor the thermo-dynamical state of the secondary metallurgy process, while Viale et al. (2007) describe the overall architecture and several interfaces of a system based on infrared camera technology to improve the process control and identify some correlations among parameters. Therefore, the potentialities of integration, connectivity, and interaction made available by Industry 4.0 revolution should be carefully considered and evaluated.

3.6 Study limitations and future research

In addition to the gaps and possible future directions pointed out above, future work could be planned for overcoming the limitations of this study. We analysed scientific articles written in English and indexed in a set of electronic databases. Therefore, we may have overlooked potential interesting studies if written in a language different from English or not indexed in the chosen databases, and technical documents and specialised sources. A deep investigation of these contributions and interactions with companies producing steel equipment could be useful for identifying further practices and defining new ones. A future collaboration with the steel companies could also be addressed to identify the main needs in the safety field after the installation of the twin LF and propose good practices able to treat the new originated risks. Future research could also be dedicated to the comprehension about the actual applicability and related benefits of the practices retrieved for traditional LFs to twin LF configurations. This would also permit understanding if and which changes are needed for assuring an effective adoption of the practices in plants equipped with a twin LF.

4. Conclusions

This paper proposes a systematic review of practices for effectively managing ladle treatments in twin or traditional LFs. We concentrate the attention on practices available in the scientific literature that allow obtaining benefits in terms of improvements on energy efficiency, environmental performance, workers' safety, and product quality. The conduction of a three-step selection process permitted retrieving 20 studies, each one presenting a different practice. We analysed them through the definition of a set of five factors regarding the practice description and kind, LF type, energetic, environmental, safety, and quality benefits, and economic savings. Furthermore, we investigate the necessary requirements for a suitable practice application. The analysis highlights an extended interest in developing mathematical models and in recycling by-products, mainly designed for traditional LFs. The increase of quality performance represents the focus of the practices, while only few studies deal with management practices for twin LFs and the improvement of health and safety of workers. These results may support companies in the selection and prioritisation of the practices to adopt, and stimulate the management practice implementation in addition to technology solutions for effectively conducting ladle treatment processes. Additionally, they provide researches with an overview of the state of the art of practices for steel ladle management and highlight the main gaps to be addressed by future research.

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