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Multi-mode acid concentration prediction models of cold-rolled strip steel pickling process

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ABSTRACT

In the steel strip pickling process, the control of the acid concentration is an important part for ensuring the strip surface quality. Now only X-ray method is used to detect the acid concentration online, but the price is very high and the maintenance is very hard. The acid concentration is not measured in most of the steel strip pickling lines online. In this paper, a soft measurement of acid concentration is developed. The pressure differential, conductivity and temperature are used to calculate the acid concentration including ferrous chloride ($FeCl_2$) and hydrogen chloride (HCl) concentration. The real pickling process is under a multi-mode condition. First, the spectral clustering based on geodesic distance is used to cluster the data into some groups. There are clearly linear relationship between the condition variables and the acid concentration. Then, orthogonal signal correction-iteratively reweighted least squares (OSC-IRLS) models based on the cluster data set are built to predict the acid concentration. The real field data set from cold-rolled strip steel pickling process is used to validate the model. The results demonstrate that the clustering method can improve the prediction result.

1. Introduction

Hot rolled steel strip is manufactured through various production processes. Iron ore and coke are fed to the blast furnace to make iron. The blast furnace is a huge chemical reactor where reduction reactions take place. The iron is then sent to the steel producing making process where bloom is produced. The steel making process consists of converters for removing carbon, refiners for adjusting elements, and continuous casters. Then, the blooming process resizes bloom to slab for the next rolling process. The strip rolling process rolls the slab to desired size [1]. In details, after hot rolling at the steelworks, the steel strip passes without interruption through a cooling process, where the steel strip is cooled to the desired temperature by spraying water on both sides of the steel. After water cooling, the strip temperature is decreased at a slower rate by cooling in air. Oxide scale is formed on the surface of the steel during the entire cooling phase. The oxide scale has to be removed from the steel surface before further processing of the steel strip, for instance cold rolling. Furthermore, the influence of defects and their removal must be considered when manufacturing to specifications that relate to certain surface quality requirements [2].

Numerous methods have been used to remove iron oxides from metal surfaces. These methods include abrasive blasting, tubling, brushing, acid pickling, salt bath descaling, alkaline descaling, and acid cleaning. The preferred method in steel production is steel pickling. A solution of either hydrogen chloride (HCl) or sulfuric acid is generally used to treat carbon steel products, while a combination of hydrofluoric and nitric acids is often used for stainless steel. This discussion focuses on carbon steel pickling operations using HCl acid. HCl acid pickling is a chemical process that uses an HCl acid solution (pickle liquor) to dissolve iron oxides from the surface of a metal without any significant attack on the steel itself. If on the one hand it is evident that high strip quality requires a complete elimination of the oxide on the strip surface, thus under-pickling cannot be tolerated, on the other hand a too long permanence of the strip in the pickling bath can lead to an erosion of the steel strip surface itself (over-pickling). Both these problems lead to more expenses or losses: in fact under-pickled strips need to be re-processed, while the quality of over-pickled ones must be downgraded [3].

In the steel strip pickling process, the control of the acid concentration is an important part for ensuring the strip surface quality. Now only X-ray method can be used to detect the acid concentration online, but the price is very high and the maintenance is very hard. Nowadays, the acid concentration is not measured online in

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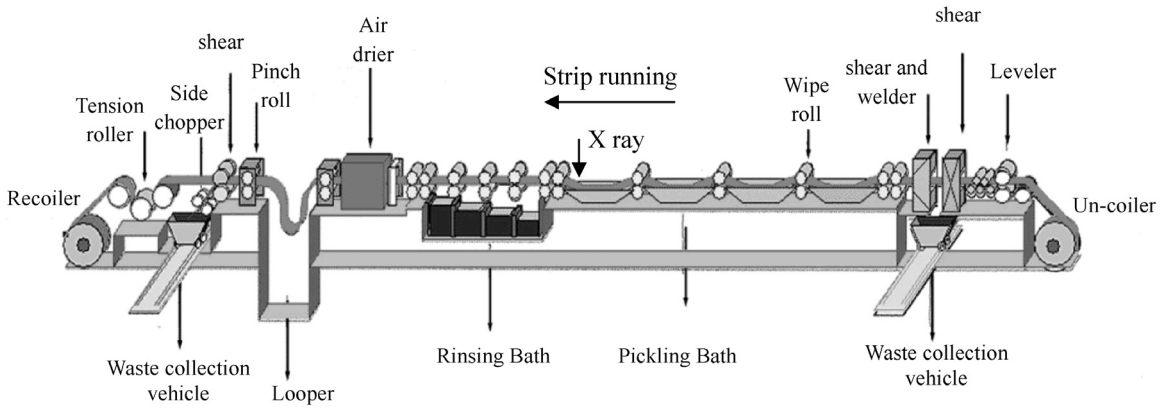

Fig. 1. Pickling process layout.

most of the steel strip pickling lines [4]. Therefore, titration analysis as a manual measurement of the acid concentration is used in the majority of the world's pickling lines. The disadvantages of the manual measurement are time delay, the acid liquid waste and human injury because of the huge quality volatility. It is very hard to build model between process parameters and acid concentration using the first principal. This article mainly analyzes the statistical correlation relationship between the strip pickling process parameters and acid concentration, and then the acid concentration soft measurement models are built [5]. In actual production process, there are different production states. First, the clustering analysis is used to distinguish the production states, then the pressure differential, conductivity and the temperature to calculate the acid concentration ($FeCl_2$ and HCl concentration). Because spectral clustering does not makes strong assumptions on the statistics of the cluster and always has good clustering results, it is selected as the clustering methods. The OSC is processed first to reduce the measurement noise and the robust regression is selected to build the relationship to decrease the impact of the isolated points. Finally, the prediction model is verified using the actual production data. In the future, according to the predicted acid concentration of pickling solution, the steel surface quality could be improved.

This paper is organized as follows. Section 2 introduces cold-rolled strip steel pickling process. Section 3 provides a detail description of spectral clustering based on geodesic distance. Section 4 introduces orthogonal signal correction and robust regression. The superiority of clustering and regression using spectral clustering and orthogonal signal correction-iteratively reweighted least squares (OSC-IRLS) is illustrated through the real data of the steel pickling process in Section 5. Finally, the conclusions are presented in Section 6.

2. Cold-rolled strip steel pickling process

During the hot rolling or heat treating of steel, oxygen from the atmosphere reacts with the iron in the surface of the steel to form a crust that is made up of a mixture of iron oxides. The presence of oxide (or scale) on the surface of the steel is objectionable when the steel is to be subsequently shaped or cold-rolled and coated. Steel pickling is widely used before cold rolling process.

The steel pickling process consists of two major steps: pickling and rinsing steps [6,7]. Continuous pickling lines for coil are capable of handling coils that are welded head to tail. The entry section comprises a coil conveyor, one or two uncoilers, one or two shears, and a welder. The uncoiler unwinds the hot coil. The shear cut the head and tail of the strip. The welder connects the primary and secondary strip. Proper trimming and welding of the strips is essential to avoid strip breaks in the line. And then the strip dips into three pickling baths of hydrochloric acid. Next the strip passes through four rinsing baths containing water to remove a remaining hydrochloric acid off the surface and then is dried with hot air. The section posterior to air drier uses a strip looper for strip storage to adapt the running velocity and then the strip is recoiled. Fig. 1 shows the pickling process.

The purpose of the pickling step is to remove surface scales and other contaminants on the metals by an immersion of the metals into an aqueous acid solution. Metals are immersed in three pickling baths in order to remove the scales from the metals. Fig. 2 gives the pickling baths schematic layout. The metals move counter current to the acid stream. The reaction occurring in the pickling baths is as follows [8]:

$$\begin{aligned} Fe_2O_3 + 6HCl &= 2FeCl_3 + 3H_2O \\ Fe_3O_4 + 8HCl &= 2FeCl_3 + FeCl_2 + 4H_2O \\ FeO + 2HCl &= FeCl_2 + H_2O \end{aligned} \quad (1)$$

In continuous pickling line, keeping acid concentration constant depends on the handling speed and the amount of removed scale due to the variable width and scale thickness. These conditions of pickling become the disturbance for controlling acid concentration, and cause the scale to remain or over pickling. In order to control acid concentration we need to use an acid concentration measuring device [9]. Because the conventional acid concentration-measuring device is a titration type analyzer offline, it requires a series process such as dilution, titration analysis under alkaline solution, neutralization, deoxidization, wasting liquid and washing after sampling an acid solution. Therefore it takes about more than 15 min to measure an acid concentration, so it is difficult to control the acid concentration to an adequate value immediately [4]. Now only X-ray method is used to detect the acid concentration online, but the price is very high and the maintenance is very hard. As an economical method to control the acid concentration online in the future, a soft measurement model is built in this paper.

3. Spectral clustering based on geodesic distance

3.1. Spectral clustering

Spectral clustering methods are widely used graph-based approaches for data clustering [10,11]. Given a dataset $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_n\}$ in R^d with k clusters, we can define an $n \times n$ affinity matrix $\boldsymbol{W}$ whose element W_{ij} can be viewed as the weight on the

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