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The Implementation of an On-line Centrifugal Casting Process Monitoring

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Ethylene cracking furnace pipe is usually manufactured by centrifugal casting process. Centrifugal casting process contains raw metal material melting and centrifugal casting. Single measurement data, including proportion of each metal element and casting temperature, can be collected for each batch, while data in time series, including surface temperatures at different locations of molding cylinder and rotational speeds, can only be obtained from centrifugal casting. Apparently, both types of data are important for final pipe quality. In this work, the span of batch process is determined according to the reading of rotation speed, therefore a batch process monitoring model is developed by multiway principle components analysis, MPCA, and principle component analysis, PCA, is employed for the feature extraction from single measurement data. Based on the cross validation by both models, a framework is proposed for the on-line centrifugal casting process monitoring. The best correct identification rate and the false alarm rate of this model are 100% and 0% respectively for studied process. The contribution plots are given to analyze forecasting results and identify root cause for failure batch, which can provide a reference for the improvement of pipe manufacturing and save the cost on penetration testing.

1. Introduction

Ethylene production technology and its capacity play a key role in a country’s economy (Yao et al., 2016). Its operation efficiency and safety have attracted great attention of state administration and public. Significant number of catastrophic accidents were triggered by equipment failure (Otegui et al., 2015). The most vulnerable part of ethylene cracking furnace is the pipes in radiation section. These pipes are manufactured by centrifugal casting process. Besides the metal components in raw material, many processing parameters in centrifugal casting (Mondal et al., 2010) are also very important to the quality of pipes, including the weight of raw materials, the casting temperature, the rotation speed of the molding pipe, and etc.

In European countries, such as Germany, centrifugal molding process is automatically executed by a machinery system, in which every step of machine movement and metal composition are well controlled; while in most developing country, such as India and China, this process is still manually conducted, by which the quality of pipes highly depends on the experience and attitude of operators. Systematic study on the contribution of operation parameters to pipe quality hasn’t been reported yet.

In order to study the impact of each processing parameter on the pipe quality, these parameters during the casting needs to be collected first, then the correlation between each processing parameter and pipe quality could be extracted, and eventually the improvement of the process could be achieved based on the study result.

Data from centrifugal casting process include both single measurement and time series, i.e., only one metal component and casting temperature are available for each batch, and molding pipe surface temperature, rotation speed can be collected during the casting process in every second. Apparently, all these parameters

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will affect the final quality of pipe. Data shall display a certain similarity for same type of pipes. If the manufacture of each pipe is considered as a batch, all single measurements of same type are equivalent to the measurements from continuous process at steady states, for which there are many statistical monitoring methods available. Principle Component Analysis (Wold et al., 1987), PCA, is one of them (Cinar et al., 2007). At the same time, the time series data from each batch have to be monitored differently. Fortunately, a PCA based method, multiway PCA (Nomikos and MacGregor, 1994), MPCA, has been developed for such a process (Todd et al., 2011). In industry, a process either belongs to continuous process, or batch process, but a centrifugal casting process seems belong to both, which make the process monitoring and fault diagnosis even more complicate. A methodology framework and reasoning protocol are needed to validate the monitoring result with both continuous and batch process characters.
In this work, monitoring methods are introduced in centrifugal casting process, and manufacturing data for two types of pipes are collected to analyze by PCA and MPCA to find the factors which influence the quality of furnace pipes. The framework for centrifugal process monitoring is proposed in section 3. Result and discussion are covered in section 4. Centrifugal casting process with monitoring methods is evaluated in the last section.

2. Centrifugal casting process and data features

The industrial furnace pipe considered in this work is manufactured by horizontal centrifugal casting. In this process, a large number of data can be collected for process monitoring.

2.1 A brief description of furnace pipe production

The diagram of centrifugal casting process is shown in Figure 1. At the beginning of the manufacturing process of furnace pipes, different raw metal materials are melted in an electric furnace. Before the molten metal is casted into a mold, cylindrical molding pipe is pre-heated and pre-coated. The molten metal is poured and cooled, while the molding pipe is rotated continuously around its horizontal-axis at the speed of 1,300 to 1,600 rpm. The molten metal is centrifugally thrown towards the inner wall of molding pipe, where it is solidified while cooling. Then penetration testing is applied to detect the possible defects including pinhole, shrinkage and crack in furnace pipes.

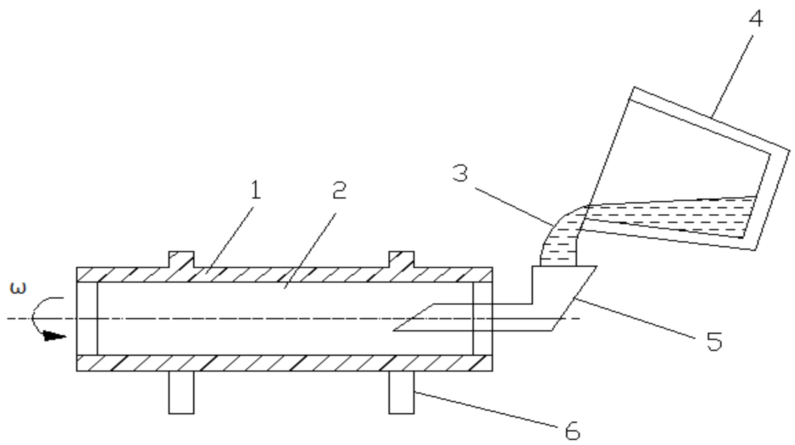


Figure 1: Centrifugal casting
1- molding cylinder 2-casting 3- molten steel 4- pouring ladel 5- pouring lip 6- centrifugal machine

2.2 The data feature of furnace pipe production

In the process of raw material melting, the materials related data in single measurement are collected. Before the molten steel in each furnace is casted, a sample taken from the molten steel is analyzed, which tells the proportion of each metal element in this furnace, including C, Si, Mn, P, S, Cr, Ni, W, Nb, Mo, Cu, Al, and Fe, which will affect pipe quality and should be kept in certain range according to the manufacturing manual. There is only one measurement available for each batch. Together with casting temperature and other measurements, these data from all batches can be considered as pseudo-continuous process measurements by replacing sampling time with batch number. On the other hand, each individual centrifugal casting process is in a typical batch mode. The data collected in this process are process related data, such as the profiles of molten steel pouring temperature, temperatures of molding pipe surface, and rotational speed of molding pipe. The data collected in this process are recorded at every second. The data feature of those variables is that they vary with time within each batch.

In order to take into account the data characteristics of the two stages, one way is to extend the single measurement to time series, which may not only increase calculation load, but also compromise feature extraction result. If only time series data are extracted to characterize the production status of the industrial furnace pipe, important process information related to raw material component and status will be lost. In order to have a more comprehensive monitoring result for this process, a method that can extract the characteristic of the two processes should be developed. This method should not only contain the information of trajectories in time series data, but also include the characteristic of single measurements.

3. Monitoring framework for centrifugal casting

In the monitoring for centrifugal casting, process data need to be validated first, during which the data for a pipe will be removed if its certain measurement is beyond the limit in manufacturing manual, usually the metal component and casting temperature, while most time series data are within the required range.

3.1 Monitoring result evaluation index

In order to evaluate model performance, The True Positive Rate (TPR) and False Alarm Rate (FAR) are defined as follows:

$$TPR = \frac{A}{M} \tag{1}$$

where A is the number of unqualified furnace pipes that correctly identified by the model, and M is the total number of unqualified furnace pipes.

$$FAR = \frac{F - A}{N - M} \tag{2}$$

where F is the total number of unqualified furnace pipes that identified by the model, thus, $F - A$ is the number of qualified furnace pipes that falsely identified by the model. N is the total number of furnace pipes that identified by the model, thus, $N - M$ is the total number of qualified furnace pipe.

3.2 Framework for process monitoring

As mentioned before, both data types need to be considered in the monitoring, therefore, both PCA and MPCA are employed for identifying quality failure.

Data in both types are put into three groups, training data, validation data and test data. Training data are used to obtain the PCA or MPCA models. Validation data is used to choose the number of principle components, by which a relative high TPR and low FAR can be obtained invalidation data.

Both PCA and MPCA are well developed statistical monitoring methods, which can be found in any text book and literatures.

The results from both models may be different. A pipe is considered unqualified if detected by either method, which will improve the identification of unqualified pipe, but may misclassify a qualified pipe. As it is more important to recognize the quality failure, this decision policy is acceptable to the manufacturer.

4. Result and discussion

There are two type of pipes are considered, as listed in Table 1. They are different in both the outer diameters, the thickness of pipe, and the content ratios of chromium and nickel in the materials. There are 4 variables in time series considered in MPCA model, which are three temperatures on the molding pipe surface and one rotation speed of molding pipe. There are 16 variables considered in PCA models, in which eleven variables are metal components, one casting temperature and four average values of time series variables considered in MPCA. Data points in each batch in MPCA starts when rotation speed reaches its maximum, 3,200 r/min, and ends when rotation speed drops from 2,000 r/min, as it can be considered as the proceeding of a casting process. Qualified pipes are referred to those past penetration test and unqualified is defined otherwise.

Training data are only from qualified pipes, while validation data and test data include both qualified and unqualified ones.

Table 1: Information of two types of industrial furnace pipe

Outer diameter/pipe thickness(mm)	Cr/Ni	Training data	Validation data (No. of qualified and unqualified pipes)	Test data (No. of qualified and unqualified pipes)	Data point in each batch for MPCA
77.2/8.1	35/45	145	12(6/6)	12(8/4)	150
68.6/7.3	25/35	126	15(8/7)	12(8/4)	150

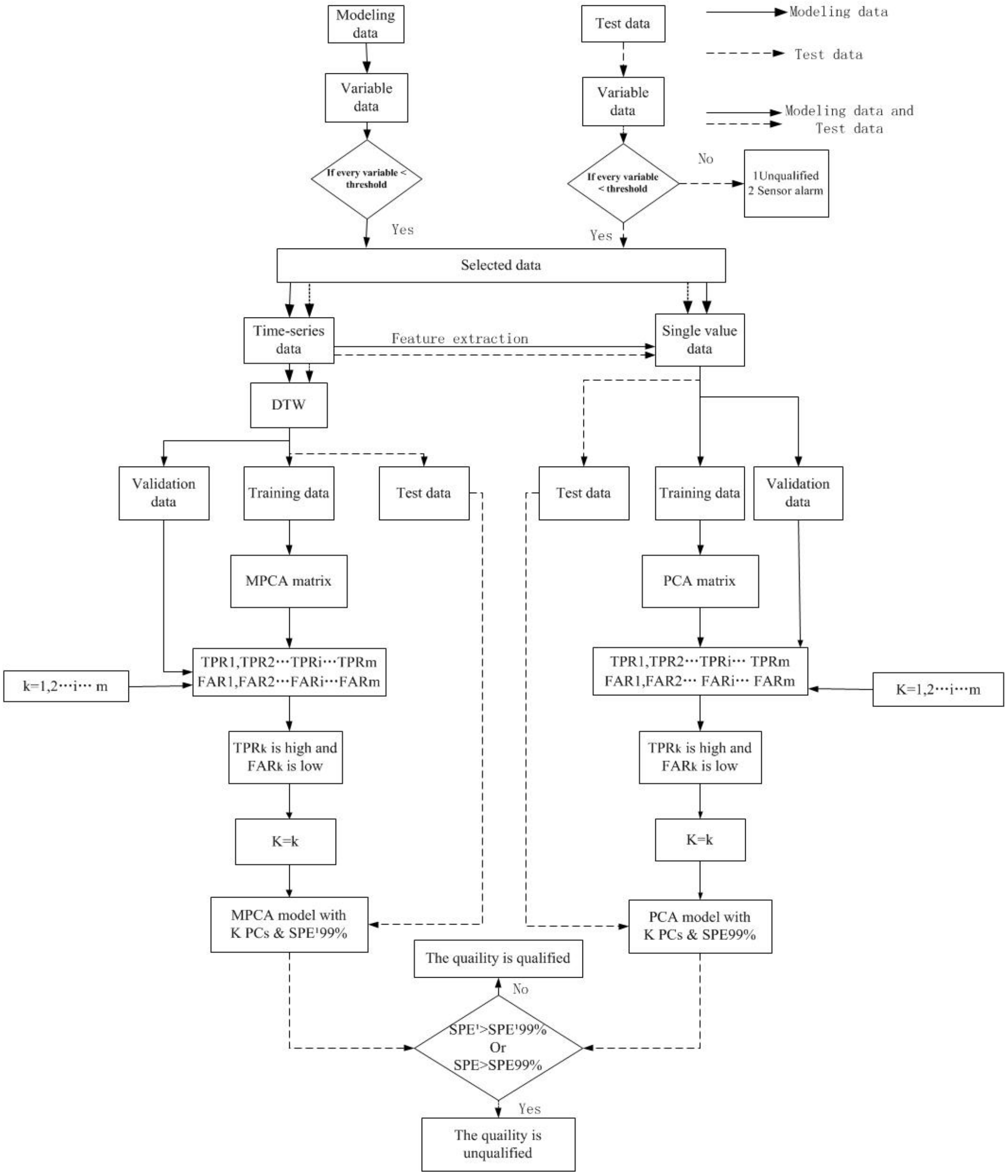


Figure 2: Flow diagram for MPCA and PCA

4.1 Model determination

Once PCA model is obtain by training data, the number of principal components are selected according to validation result, which should give relative high TPR and low FAR. For pipe with the outer diameter of 77.2

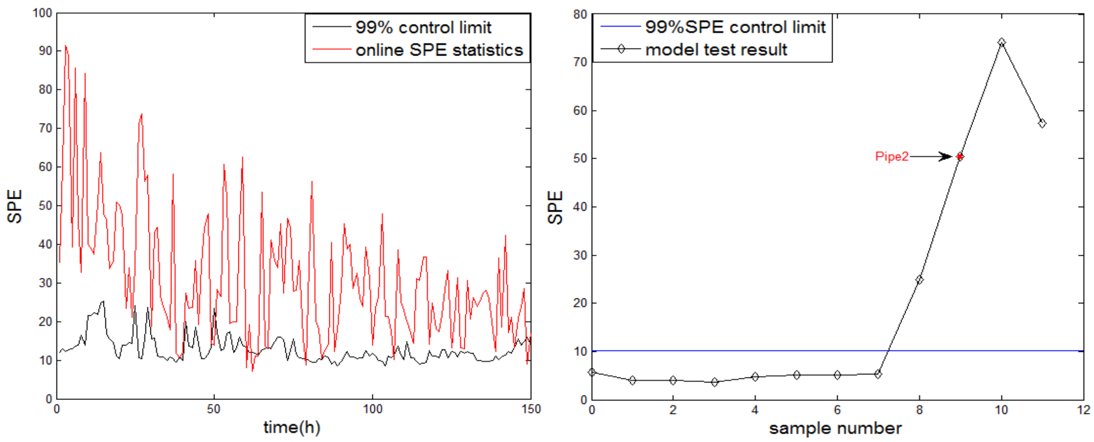
mm, there are 1 principal component for MPCA, under which TPR is 100 % and FAR is 0, and 2 for PCA, under which TPR is 83.3 % and FAR is 0; while, for the pipe with outer diameter of 66.8 mm, 1 for MPCA, under which TPR is 75% and FAR is 12.5 %, and 5 for PCA, under which TPR is 100 % and FAR is 0.

4.2 Monitoring result and discussion

Test result for both types of pipes are listed in Table 2. It can be seen that only one unqualified pipe hasn't been detected by PCA method for the pipe with outer diameter of 77.2 mm, but it is clearly identified by MPCA method. As mentioned above, a pipe will be classified as unqualified if it is detected by either MPCA or PCA as abnormal. Thus, all failure pipes can be correctly identified. It also shows that the trajectory of temperature is important to the pipe quality, even its average is within the required range of production manual. On the other hand, metal components can be only considered in PCA model, so PCA model is also very necessary for the monitoring system.

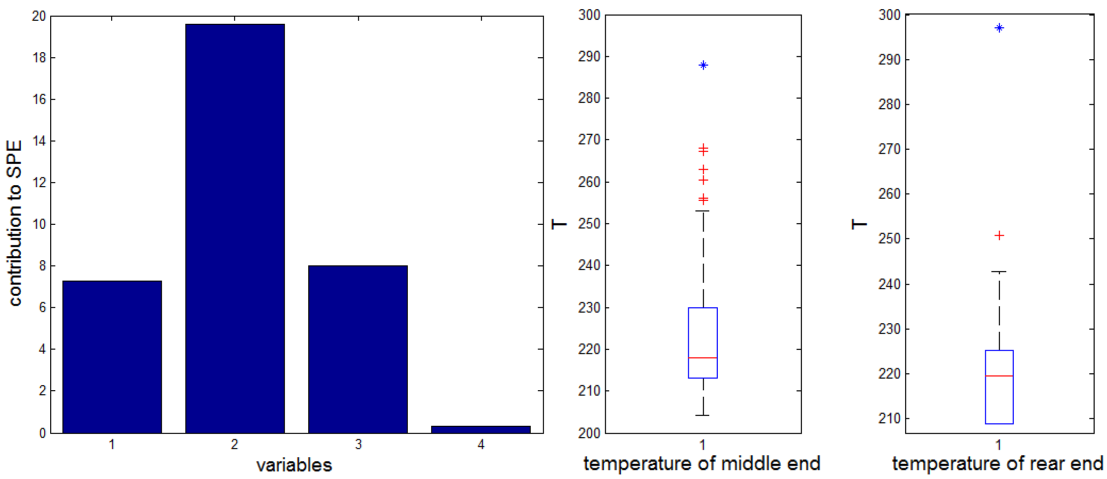
Table 2: Test result of pipe quality monitoring for both types of pipes

outer diameter/pipe thickness(mm)	No. of unqualified pipes identified correctly (MPCA/PCA)	TPR (MPCA/ PCA)	No. of qualified pipes misidentified (MPCA/PCA)	FAR (MPCA/PCA)	TPR/FAR based on both MPCA and PCA
77.2/8.1	4/3	100%/75%	0/0	0/0	100%/0
68.6/7.3	4/4	100%/100%	0/0	0/0	100%/0



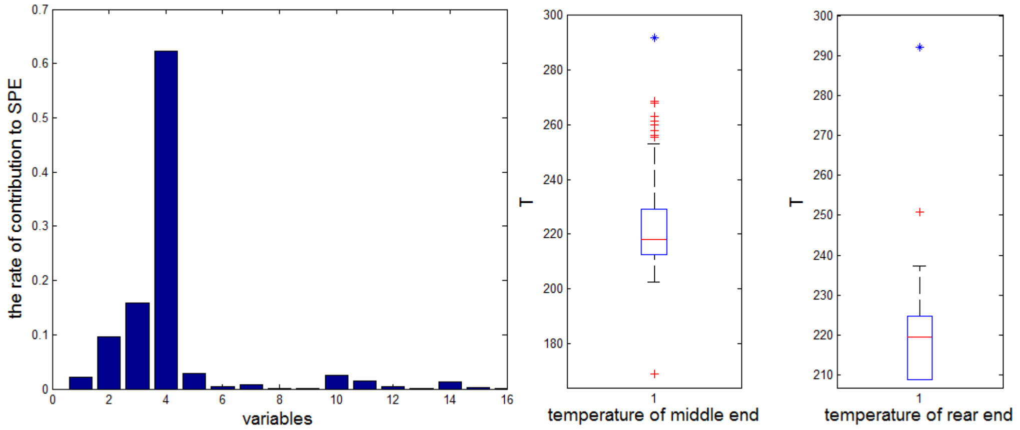
a From MPCA *b From PCA*

Figure 3: Test result of both MPCA and PCA for pipe 2 with the outer diameter of 68.6 mm



a *b*

Figure 4: Contribution plot a and box plot b of MPCA for failure pipe 2 with the diameter of 68.6 mm



a b

Figure 5: Contribution plot a and box plot b of PCA for failure pipe 2 with the diameter of 68.6 mm

The result for a failure pipe 2 is discussed as an example. It can be seen from Figure 3b that all failure pipes are correctly identified. Both test results of MPCA and PCA are illustrated in Table 3. In order to trace back the key factor resulting the failure in pipe quality, the contribution plot and box plot of MPCA for failure pipe 1 with the diameter of 66.8 mm are shown in Figure 3 and those of PCA are shown in Figure 4. It can be seen in both Figure 3a and Figure 4a, the key contribution for the failure is isolated as the surface temperature of molding pipe at the end position. According to the box plot in Figure 3b and Figure 4b, the rear end temperature is much higher than that of other pipes, which could be resulted from the insufficient cooling before the casting.

5. Conclusions

In this work, a frame for monitoring centrifugal casting process, which incorporates not only the single measurements, but also those in time series. Both MPCA and PCA models are developed and validated for two types of pipe based on the industrial data. Test result shows that proposed method can efficiently identify the quality failure and isolate the root cause.

Due to the current instrumentation setting of the centrifugal process, only a limited number of variables are monitored in this system, e.g. steel weight, vibration replacement, and mechanical process procedure, while any processing information before the penetration test will affect the result of penetration test. Furthermore, further X-ray check will be performed after penetration test, which means more signals needed to determine the final product quality. Framework shall be upgraded accordingly when more variables are available.

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