Individual Station Monitoring Using Press Tonnage Sensors for Multiple Operation Stamping Processes

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In multiple operation stamping processes, a press tonnage signal measured by press tonnage sensors installed on press linkages/uprights, is the summation of die forces at all stations. Different from the current practice of using a whole cycle of press tonnage signals to monitor the compound condition of all stations, this paper proposes a new method to use the partitioned monitoring segments of press tonnage signals to monitor individual station conditions. For this purpose, a generic signal segmentation principle is proposed, and the Hotelling T^2 control charts are developed with consideration of the interactions among stations. A real case study of a doorknob stamping process is provided to demonstrate analysis procedures and effectiveness of the developed methodology. [DOI: 10.1115/1.1643749]

1 Introduction

Multiple operation stamping processes consisting of transfer or progressive dies have been becoming increasingly popular due to their high productivity, high precision, and low manufacturing cost. In such a process, there are multiple die stations working simultaneously to produce a part. The current practice to monitor individual stations mainly relies on in-die tonnage sensors, which are placed inside of each die to capture the stamping force within individual stations. In general, the approach of using in-die tonnage sensors requires extra initial costs in sensor investment and sensor installation, needs continuous costs for frequent sensor-related maintenance, and causes more complexity in die change. Therefore, in-die tonnage sensors for stamping process control still have very limited applications in stamping industry.

Press tonnage sensors, which are the strain gages mounted on the press uprights or linkages, have been recently available in many stamping press machines in industry. The stamping forces measured by press tonnage sensors are called *press tonnage signals*, which is the sum of the stamping forces exerting on all dies. With the rapid development of sensor technology and tonnage monitoring systems [1–4], tremendous efforts have been made on using online press tonnage signals for process condition monitoring. Examples of those accomplishments include (a) press condition monitoring to reduce setup time and detect the change of shut height, bearing wear, and nitrogen cushion pressure [1,5–7]; (b) tool condition monitoring to detect the punch worn-out [8,9]; and (c) blank material monitoring to detect the change of blank thickness and hardness [10,11]. Recently, increasing research efforts have been devoted to fully utilizing the waveform features in the whole cycle of press tonnage signals to improve the diagnosability. For example, Jin and Shi [12,13] developed feature preserving data compression method and in-process diagnostic performance improvements using wavelets, Koh et al., and Robbins [5–7,10] studied the feature extraction method for waveform signals. However, all these research achievements mainly focus on single operation stamping process, or a tandem press. In these cases, only a single die is working in the process, thus, the change of press tonnage signals reflects the change of the die force within a single station without compounding with other stations. Therefore, the press tonnage signals can be directly used for the die condition monitoring.

In a multiple operation stamping process, a press tonnage signal is the sum of the stamping forces exerting on individual dies of all stations, that is, a press tonnage signal is the compound of all die forces at all stations. Therefore, the press tonnage signals cannot be directly used for individual station monitoring. In this paper, a new methodology is developed to explore the potential possibility of utilizing press tonnage signals for individual station monitoring. Different from the current practice of using a whole cycle of press tonnage signals to monitor the compound conditions of all stations, the paper uses the partitioned monitoring segment of press tonnage signals to monitor the interested individual stations. The paper is organized as follows: after the introduction, an overview of the proposed methodology will be given in Section 2, and the detailed analyses for the methodology development will be presented in Section 3. Afterwards, a real case study of a doorknob stamping process is discussed in Section 4 to illustrate the analysis procedures and demonstrate the effectiveness of the proposed methodology. Finally, the paper is concluded in Section 5.

2 Methodology Overview

In a multiple operation stamping process with either a transfer or progressive die, multiple stations work together to produce one or more parts in every press stroke/cycle. In general, during each press stroke, each upper moving die hits the corresponding stationary lower die only within a certain range of press crank angles [14]. Each of those crank angle ranges is called the *working range* of the corresponding station. When a failure occurs at an individual station, the press tonnage signal will only partially change at the segment corresponding to the working range of the failed station. Therefore, it is possible to find some isolated segments so that each segment is only relevant to the working ranges of one station or a small group of stations of interest. Such an isolated segment is called as *monitoring segment* for the monitored stations in the paper. If such a monitoring segment exists, the interested station can be monitored through online change detection of press tonnage signals at the monitoring segment. Based on this principle, a generic analysis method will be developed in this paper to judge the existence of the monitoring segments. Then, monitoring control charts will be developed to online detect the waveform change of the press tonnage signals at each monitoring

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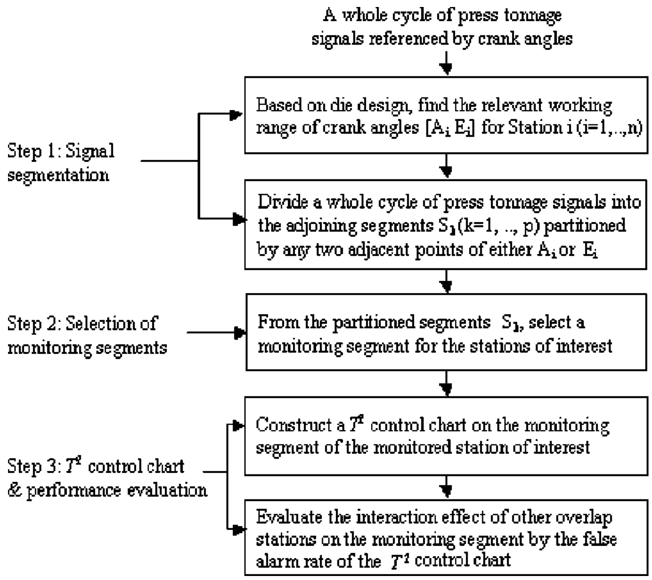

Fig. 1 Analysis framework for multiple-operation stamping process monitoring

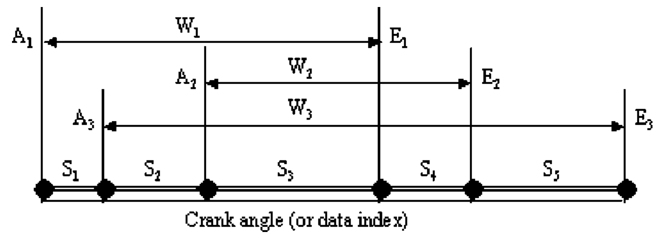

Fig. 2 Segmentation of a whole cycle of signals

segment. The framework of the proposed methodology consists of three-step analyses as shown in Fig. 1 (The detailed definition of each notation used in Fig. 1 will be given in Section 3.1):

(1) *Signal segmentation*: Segmentation is conducted to divide a whole cycle of a press tonnage signal into a set of adjoining segments, each of which contains one or several same stations over the partitioned segment. (2) *Monitoring segment selection for the interested individual or a small group of stations*: Based on the understanding of a process, a monitoring segment will be selected from the partitioned segments so that the change of the press tonnage signal at the selected monitoring segment is the reflection of the condition change of the monitored station. (3) *Monitoring control chart development and performance evaluation*. Hotelling T^2 control charts are developed on each monitoring segment to monitor the conditions of each interested station or a small group of interested stations. If it is inevitable for other unmonitored stations overlapping with the monitored stations at the monitoring segment, their interaction effects need to be considered. In this paper, the impacts of those overlapping stations are evaluated by the change of the false alarm rate of the T^2 control chart. The details of each step analysis will be discussed in Section 3.

3 Methodology Development

3.1 Segmentation of Press Tonnage Signals. Segmentation of press tonnage signals consists of dividing a whole cycle of press tonnage signals into a set of adjoining segments, each of which involves the same working stations over the partitioned segment. Under this partition, if a signal change is detected at a given segment, the search of the possible failure stations can be limited to a few stations that are included at this monitoring segment, rather than all stations in the process. Therefore, monitoring of a partitioned segment of press tonnage signals can explicit the diagnosis of the location of the failed stations. In addition, the signal to noise ratio at the monitoring segment is increased for the monitored stations. This is because the signal change due to other unmonitored stations, which should be considered as the noise for the monitored stations, are excluded from the monitoring segment.

In order to conduct segmentation of press tonnage signals, the working range of each station should be known. If the timing-charts in the die design are available for a multiple operation process, the working range of each station can be determined directly from the die timing-chart. If the die timing-chart is not available, a special tonnage decomposition test can be conducted to obtain the decomposed tonnage signals of individual die forces and further to determine the working ranges of individual stations [15]. Thus, it is reasonable to assume that the information of the working range of each station is available for a given process. Under this condition, a general segmentation principle can be developed.

The following example is given to illustrate the segmentation principle. A stamping process as shown in Fig. 2, has three working stations. The working range of each station is known and denoted as W_i $(i=1,2,3)$. The corresponding boundary of each station is indicated as the start point (A_i) and the end point (E_i) respectively. In this case, five segments S_k $(k=1,\ldots,5)$ are partitioned by using any two adjacent points of either A_i or E_j $(i,j=1,2,3)$. Thus, the whole cycle of signals relating to all stations is divided into five segments in which each segment consists of the same working stations.

The segmentation results in Fig. 2 show that S_1 and S_5 are only relevant to station W_1 and station W_3 respectively. In this situation, if the press tonnage signal change is detected at S_1 (or S_5), the possible failure station is only one station W_1 (or W_3). So, the monitoring segment for station W_1 (or W_3) is selected as segment S_1 (or S_5).

In the selection of the monitoring segment for station W_2, it is inevitable to involve at least two stations of W_2 and W_3 at the relevant segments S_4. However, segment S_4 can still be used as a monitoring segment for station W_2 if it satisfies one of the following two conditions: (1) the compound monitoring result for both stations of W_2 and W_3 is sufficient in a specific application; (2) the change of stamping force due to the failures at the unmonitored station W_3 is not significant at segment S_4. The detailed discussion on the monitoring segment selection and justification will be given in Sections 3.2.2 and 3.2.3.

It can be seen that the partitioned results of the segments and their boundaries will be varied with different processes, which are determined by the number of stations and the working range of each station in a given process. However, the proposed segmentation principle can be generalized as the following two-step implementation procedures, which are applicable to any multiple operation stamping processes if the knowledge of the working range of each station is available.

(1) The working range of each station i is marked on a whole cycle of the press tonnage signals by a start point (A_i) $(i=1,\ldots,n$; n is the total number of working stations in the process) and an end point (E_i) using either press crank angles or data sampling indices.

(2) The partition boundary of each segment is defined by any two adjacent points using either a start point (A_i) or an end point (E_j) $(i,j=1,\ldots,n)$.

3.2 Process Monitoring Based on Monitoring Segments of Press Tonnage Signals. In order to monitor the change of waveforms of the press tonnage signals, a multivariate Hotelling T^2 control charts will be developed on each monitoring segment for the interested stations. In this section, a brief overview of Hotelling T^2 control charts is given in the next Subsection 3.2.1. Afterwards, the guideline of monitoring segment selection is given in

Subsection 3.2.2. The interaction effect of other unmonitored stations on the monitoring segment is quantitatively evaluated in Subsection 3.2.3.

3.2.1 Hotelling T^2 Control Chart for Detection of Signal Profile Changes. Hotelling [16] provided the first solution to the multivariate monitoring problem by suggesting the use of the T^2 statistic. In this paper, the press tonnage signals are assumed following a multivariate normal distribution. For a single observation, the T^2 statistic is defined on the monitoring segment of a press tonnage signal as:

$$T^2=(\mathbf{x}_i-\overline{\mathbf{x}})^T\mathbf{S}^{-1}(\mathbf{x}_i-\overline{\mathbf{x}}) \tag{1}$$

where $\mathbf{x}_i \in R^{p\times 1}$ is the ith observation vector with p measurement data points included in the monitoring segment, and $\overline{\mathbf{x}} \in R^{p\times 1}$ is the mean vector estimated from the preliminary in-control m samples of press tonnage signals at the monitoring segment, that is, $\overline{\mathbf{x}}=[\overline{x}_1,\overline{x}_2,\cdots,\overline{x}_p]^T$, and $\overline{x}_j$ $(j=1,\ldots,p)$ is the average of m samples at measurement point j of the press tonnage signal, and $\mathbf{S}$ is the estimated covariance matrix of m samples.

Alt [17] has pointed out that there are two distinct phases in constructing the Hotelling T^2 control limits. Phase I control limits are used to check the preliminary samples to obtain in-control data for estimation of $\overline{\mathbf{x}}$ and $\mathbf{S}$. Phase II control limits are used to check whether incoming production data are in control. For a prespecified Type-I error α, the Phase II upper and lower control limits are developed by Tracy et al. [18]:

$$LCL_2=K\cdot F_{1-\alpha/2}(p,m-p), \quad \text{and} \quad UCL_2=K\cdot F_{\alpha/2}(p,m-p) \tag{2}$$

where the constant K is $K=p(m-1)(m+1)/m(m-p)$, and $F_{\alpha/2}(p,m-p)$ is the $1-\alpha/2$ percentile of the F distribution with p and $m-p$ degrees of freedom.

3.2.2 Selection of Monitoring Segments for Individual Station Monitoring. In order to monitor individual station conditions, a T^2 control chart is constructed on each monitoring segment of press tonnage signals. The basic principle for monitoring segment selection is that the decision of a T^2 control chart constructed at the monitoring segment should be able to reflect the true condition of the monitored station. Based on this principle, the first effort is usually to select a monitoring segment that involves only one monitored station. If this result cannot be achieved due to the process design, the next effort is to select a monitoring segment in which the press tonnage signal is mainly contributed by the monitored station with the least involvement of other stations as possible.

In summary, the selection of a monitoring segment is to sequentially judge if the segment satisfies one of the following two conditions: (i) The segment only involves the monitored station. This condition requires no overlap at the monitoring segment between the working range of the monitored station and that of other unmonitored stations. (ii) The segment involves the fewest number of other unmonitored stations, and the change of press tonnage signal due to the failure at other unmonitored stations is not significant at this monitoring segment. A method for quantitative check of this significance level will be presented in Subsection 3.2.3. A real example of the doorknob stamping process will also be provided to illustrate the implementation in Section 4.3.

It is worth pointing out that if a monitoring segment does not exist in the given process for each individual station monitoring, the compound monitoring results using the selected segment is still more beneficial than that using a whole cycle signal. This is because the search of the possible failure stations can be limited to a few stations involved at that segment rather than all stations in the process. If this compound monitoring result is not sufficient for an application, in-die sensors are needed to further separate the tonnage signals for those stations that are compounding at the monitoring segment. In this sense, the method for judging the monitoring segment can also be used to determine if in-die sensors are really needed. For those stations in which a monitoring segment can be found for individual station monitoring, there is no need to install in-die sensors. Thus, the elimination or reduction of in-die sensors can be achieved by using the segmental monitoring of press tonnage signals. As a general rule, the use of monitoring segments are more appealing for station monitoring in a multiple operation process than the use of a whole cycle signal, unless all monitored stations are exactly overlapping throughout all segments.

3.2.3 Analysis of False Alarm Rate for Individual Station Monitoring. In design of a T^2 control chart, a multivariate normal distribution is assumed in the paper for press tonnage signals. So, a hypothesis testing H_j is defined for station j as:

$$\text{Null Hypothesis:} \quad H_j=0, \quad \text{i.e.,} \quad \boldsymbol{\mu}(j)=\boldsymbol{\mu}_0(j);$$

$$\text{Alternative Hypothesis:} \quad H_j=1, \quad \text{i.e.,} \quad \boldsymbol{\mu}(j)\neq\boldsymbol{\mu}_0(j).$$

where $\boldsymbol{\mu}_0(j)$ is the mean vector of the monitoring segment of station j when all stations are in control (i.e. a referenced normal condition signal for station j is defined as the press tonnage signal at the monitoring segment when all stations are in-control). $\boldsymbol{\mu}(j)$ is the corresponding mean vector of incoming press tonnage signals at the monitoring segment during production. Please note the subscript j in H_j is specially used as an index of the monitored station, and the binary values of H_j are used to represent two different conditions of the monitored station j in the hypothesis testing (i.e., $H_j=0$ as an in-control normal condition, and $H_j=1$ as an out-of-control failed condition).

The monitoring decision made by the T^2 control chart on the monitoring segment is used to represent the operational condition of the corresponding monitored station. During the process monitoring, the false alarm rate α_j of station j monitoring should be defined by $\alpha_j=P\{D_j=1|H_j=0\}$, where D_j represents the T^2 control chart decision based on the monitoring segment of station j ($D_j=0$ as no alarm, i.e., unable to reject $H_j=0$; and $D_j=1$ as an alarm with rejection of $H_j=0$). Based on this definition, it can be seen that if the monitoring segment of station j overlaps with the working range of other stations, the false alarm rate for station j monitoring will be affected by those overlapping station conditions. The reason for this is that a failure occurring at those overlapping stations could cause a signal change at the monitoring segment of station j, thus misleading to $D_j=1$ even though station j is in-control. Therefore, the true false alarm rate for station j monitoring, i.e., $\alpha_j=P\{D_j=1|H_j=0\}$ will be different from the Type I error α specified in the control limit of Eq. (2), i.e., $\alpha=P\{D_j=1|H_k=0,k=1,\ldots,n\}$. So, the true false alarm rate for station j monitoring should be reevaluated to consider the interaction effect of all other unmonitored stations on the monitoring segment. The detailed analysis is conducted as the following two steps:

(1) False alarm rate analysis with consideration of interaction effects among stations

(1.1) Definition of the true false alarm rate α_j of station j monitoring

Considering the interaction effects of all other unmonitored stations on the monitoring segment, the true false alarm rate α_j of station j monitoring should be calculated by:

$$\alpha_j=P\{D_j=1|H_j=0\}=\sum_{i=0}^{2^{n-1}-1} P\{D_j=1|(H_j=0)\cap B_i\}\cdot P(B_i) \tag{3}$$

where $B_i=[H_nH_{n-1}\cdots H_{j+1}H_{j-1}\cdots H_1]$ represents the true condition of all other stations except station j (normal or failed depending on whether $H_k=0$ or 1, $k=1,\ldots,n$ and $k\neq j$). Thus, B_i can be defined as a binary code with $B_0=[00\cdots00\cdots0]$ and $B_{i+1}=B_i+1$. Under this notation, B_i $(i=0,1,2,\ldots,2^{n-1}-1)$ forms the complete events of all combinations of the unmonitored

Table 1 Illustration of using B_i to represent the station conditions

I	$B_i=[H_nH_{n-1}\cdots H_{j+1}H_{j-1}\cdots H_3H_2H_1]$ (as binary code)	Station conditions
0	[00…00…000]	No failure at all other unmonitored stations
1	[00…00....001]	Only the 1st station has a failure
2	[00…00…010]	Only the 2nd station has a failure
3	[00…00…011]	Only the 1st and the 2nd station have failures
…	…	…
$2^k-1(k<j)$	$[\underbrace{00...0}_{n-k-1}\underbrace{11...1}_{k}]$	All first k stations have failures
$2^k(k>j)$	$[\underbrace{00..01}_{n-k-2}\underbrace{0...0}_{k}\}$	Only the $(k+1)^{\text{th}}$ station has failure
…	…	…
$2^{n-1}-1$	[11…11…111]	All stations (except the j^{th} station) have failures

station conditions. Thus, $P(\cup_{i=0}^{2^{n-1}-1}B_i)=1$ and $B_k\cap B_i=\phi$ for $k\neq i$. The representation of the individual station conditions using B_i is illustrated in Table 1.

(1.2) Difference between the true false alarm rate α_j and the pre-specified Type I error α

The false alarm rate of station j monitoring in Eq. (3) can be obtained as

$$\alpha_j=\alpha\cdot p_j(0)+\sum_{i=1}^{2^{n-1}-1}\gamma_j(i)p_j(i),\quad (j=1,2,\ldots,n) \tag{4}$$

where α is the Type I error specified in the T^2 control chart of Eq. (2), that is,

$$\alpha=P\{D_j=1|(H_j=0)\cap B_0\} \tag{5}$$

$\gamma_j(i)$ represents the false alarm probability due to the interaction of other unmonitored stations under the failed conditions, that is,

$$\gamma_j(i)=P\{D_j=1|(H_j=0)\cap B_i\}\quad (i\neq 0) \tag{6}$$

Also, $p_j(i)=P(B_i)$ is used to include the index of the monitored station j. For $i\neq 0$, $p_j(i)$ represents the probability of event B_i in Table 1 with the failures occurring at the unmonitored stations. For $i=0$, $p_j(0)$ represents the probability of all unmonitored stations under the in-control normal condition.

(1.3) Discussion of the conditions for $\alpha_j=\alpha$

From Eq. (4), it can be seen that only under the following two special cases, the true false alarm rate α_j of station j monitoring can be equal to the pre-specified Type I error α.

(1) For $i\neq 0$, $p_j(i)=0$. In this case, $p_j(0)=1$ since $P(\cup_{i=0}^{2^{n-1}}B_i)=1$. Thus, $\alpha_j=\alpha$. This condition implies that the probability of failures occurring at any of the unmonitored stations is close to zero, that is, the probability of all unmonitored stations under the normal condition is close to one. This condition is approximately satisfied when all unmonitored stations have near zero failure probability.

(2) $\gamma_j(i)=\alpha$ i.e., $P\{D_j=1|(H_j=0)\cap B_i\}=P\{D_j=1|(H_j=0)\}$. In this case, $\alpha_j=\alpha\cdot p_j(0)+\Sigma_{i=1}^{2^{n-1}-1}\gamma_j(i)p_j(i)=\alpha\cdot p_j(0)+\Sigma_{i=1}^{2^{n-1}-1}\alpha\cdot p_j(i)=\alpha$ since $\Sigma_{i=0}^{2^{n-1}-1}p_j(i)=1$. In order to satisfy this condition, it requires the conditions of all unmonitored stations do not affect the press tonnage signal at the monitoring segment of station j. This condition can be satisfied if the working ranges of all unmonitored stations do not overlap with that of station j.

In general, if neither of above cases exists, then the true false alarm rate needs to be reevaluated by considering the interaction effect of the unmonitored stations on the monitoring segment. When n is large, it is generally not easy to consider all events B_i in Eq. (4). However, in practice, Eq. (4) can be significantly simplified by ignoring those unmonitored stations which satisfy one of the following two conditions: (1) their working ranges start after, or finish before, the jth monitoring segment, that is, their working ranges have no overlaps with that of the monitored stations; (2) they have a near-zero failure probability. In this case, little probability of their failures will cause a signal change at the monitored segment leading to a false alarm for the monitored station. Usually, after checking above two conditions, only a few unmonitored stations need to be included in Eq. (4). The detailed analysis of the effect of those remaining stations is given as follows.

(2) Impact of the failed station k on the false alarm rate of station j ($k<j$) monitoring

If there is a failure at station k affecting the monitoring segment of station j, the distribution of the T^2 statistic at the monitoring segment j is changed under event B_i $(i\neq 0)$, which is associating with the failure at station k. Thus,

$$T_\delta^2=(\mathbf{x}_i-\overline{\mathbf{x}})^T\mathbf{S}^{-1}(\mathbf{x}_i-\overline{\mathbf{x}})=(\mathbf{x}_i-\overline{\mathbf{x}}_f+\Delta\hat{\boldsymbol{\mu}})^T\mathbf{S}^{-1}(\mathbf{x}_i-\overline{\mathbf{x}}_f+\Delta\hat{\boldsymbol{\mu}}) \tag{7}$$

where $\overline{\mathbf{x}}_f$ is the signal mean vector when event B_i occurs $(i\neq 0)$. $\Delta\hat{\boldsymbol{\mu}}=\overline{\mathbf{x}}_f-\overline{\mathbf{x}}$ is the change of the signal mean due to the interaction effect of event B_i at the monitoring segment. It is proven that the statistic T_δ^2 in Eq. (7) follows a noncentral F distribution (Please see the appendix for the detailed proof):

$$T_\delta^2/K\sim F(p,m-p,\delta) \tag{8}$$

where $F(p,m-p,\delta)$ is the noncentral F distribution with the degrees of freedom p and $m-p$, and the non-centrality δ and the constant K are defined in the appendix.

If the initial monitoring control limits of UCL_2 and LCL_2 in Eq. (2) are established under the specified Type I error α when all stations are in control, the true false alarm rate of station j motoring using this T^2 control chart will be generally larger than α. The amount of $\gamma_j(i)$ due to event B_i can be calculated by:

$$\begin{aligned}\gamma_j(i)&=P(T_\delta^2>UCL_2)+P(T_\delta^2<LCL_2)\\&=P[T_\delta^2/K>F_{\alpha/2}(p,m-p)]\\&\quad+P[T_\delta^2/K<F_{1-\alpha/2}(p,m-p)]\end{aligned} \tag{9}$$

Thus, the total increase of the false alarm rate will be:

$$\begin{aligned}\Delta\alpha_j&=\alpha\cdot p_j(0)+\left[\sum_{i=1}^{2^{n-1}-1}\gamma_j(i)\cdot p_j(i)\right]-\alpha\\&=\sum_{i=1}^{2^{n-1}-1}(\gamma_j(i)-\alpha)\cdot p_j(i)\end{aligned} \tag{10}$$

From Eq. (9), it can be seen that the increase of the false alarm rate will be affected by the mean change at the monitored segment due to event B_i. If there is no effect of event B_i on the monitoring segment, then $\delta=0$ leading to $\gamma_j(i)=\alpha$. Also, $p_j(i)$ represents the probability of the given event B_i, which is the weight of how the failure probability of the unmonitored stations affect the decision on the monitored station j in Eq. (10). The value of $p_j(i)$ can be calculated from the historical data, or assigned based on the designed process reliability.

4 Case Study

4.1 Brief Description of the Doorknob Stamping Process A doorknob stamping process is used as a real example to demonstrate the proposed methodology. The finished doorknob part is shown in Fig. 3. A multiple operation stamping process is used in the production, which includes seven individual working dies with a sequence of: (1) notch, (2) cutoff, (3) blanking, (4) draw, (5) redraw, (6) the 2nd redraw, and (7) bulging. Among these seven dies, the notch and cutoff dies are combined together in one station to make a notch shape on the continuous coil and then cut each workpiece off from the coil. A circular workpiece is further cut out at the blanking station. After that, the part shape is progressively formed by three draw stations (draw, redraw and the 2nd redraw) and finally extruded at the bulging station. A sketch of the intermediate parts after each operation is also illustrated in Fig. 3. The following subsections will illustrate the details of the methodology implementations for individual station monitoring.

4.2 Signal Segmentation. In this case study, there is no accurate die timing-chart available from the die design. The working range of each station is determined from the decomposed tonnage signals of each station force as shown in Fig. 4. These decomposed tonnage signals are obtained from an offline tonnage decomposition test [15].

Based on the segmentation principle proposed in Section 2.1, two-step implementation procedures are performed as follows: (a) mark the start point A_i and the end point E_i for each working die $W_i\,(i=1,\ldots,7)$. The operation name of each W_i can also be found from the first column of Table 2. (b) the divided segment $S_k\,(k=1,\ldots,10)$ is partitioned by any two adjoining points of either A_i or $E_j\,(i,j=1,\ldots,7)$. The segmentation results are also summarized in Table 2. The end point of each segment is listed in the second row and the third row, which are referenced by the data indices and the press crank angles respectively. The start point of segment 1 is the first measurement point referenced by data index=1 or press crank angle=123.0°. The sampling interval in

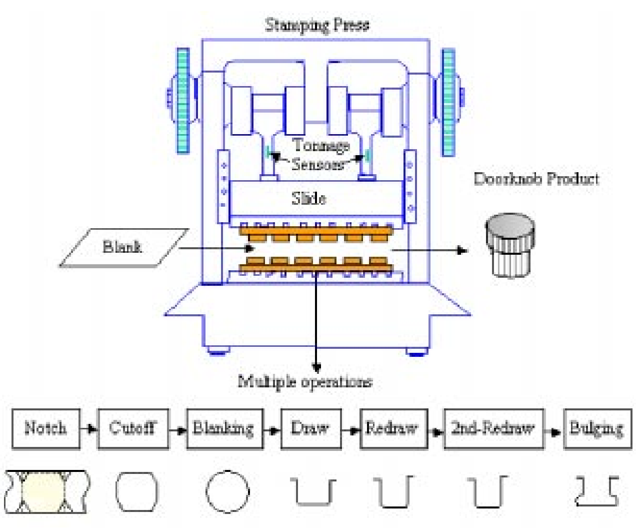

Fig. 3 Multiple operations in the doorknob stamping process

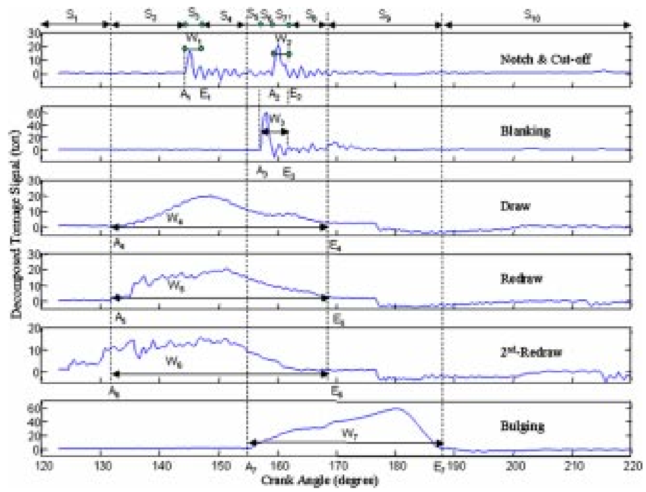

Fig. 4 The decomposed individual signals at each working station

terms of the press crank angle is equal to 0.35°. Table 2 also summarizes the correspondence between the working stations and the partitioned segments, where the segments covered by the dash line indicates the working range of each station, and the segments covered by the solid line indicates the range of the monitoring segment. The selection of those monitoring segments will be discussed in the next subsection.

4.3 Determination of the Monitoring Segment for Each Station. For performing individual station monitoring, the monitoring segment needs to be selected for each station within its working range. As discussed in Section 3.2.2, the monitoring segment should be selected in such a way that the minimum number of other overlapping stations is included in the monitoring segment. In this doorknob process, the details for determination of the monitoring segments for those station monitoring are discussed below:

(1) In the notch and cut-off station, segments S_3 and S_7 are selected as the monitoring segments for the notch operation and the cutoff operation respectively because S_3 or S_7 is the only segment covered by the working range of these two operations. Therefore, for notch and cutoff operations shown by row 4 and row 5 in Table 2, the solid lines of the monitoring segment cover the same range of the dashed lines of the working range of each operation.

(2) In the blanking station shown by row 6 in Table 2, its working range indicated by dashed lines covers only two segments of S_6 and S_7. Segment S_6 is selected as the monitoring segment because segment S_6 as shown in Fig. 4 covers the first peak tonnage of the blanking operation, which contains the critical characteristics of the blanking station conditions. Also, segment S_6 has no overlap with the cutoff station.

(3) In three draw stations (draw station, redraw station, and the 2nd redraw station), a compound monitoring segment has to be used for monitoring of all three stations together because they have the same working range and have the same characteristics of the draw operation as shown in Fig. 4. From Fig. 4, it can also be seen that among their working ranges (from segment S_2 to segment S_8), segments S_2 and S_4 contain only three draw stations without overlapping with other stations. Furthermore, segment S_2 is selected as the monitoring segment for three draw stations because it is the draw-die forming action range containing more critical information than segment S_4 which is the releasing range after draw operation. It should be noticed that the monitoring result from the T^2 control chart on segment S_2 is the compound condition of all three draw stations rather than that of each draw

Table 2 Signal segmentation and profile characteristics (— — — working range, —— monitoring range)

Segment	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
End Point (Data Index)	26	63	70	92	99	105	113	131	187	285
End Point (Crank Angle)	131.7	144.8	147.2	155.0	157.4	159.5	162.3	168.7	188.3	222.8
Notch			— — — / ——							
Cutoff							— — — / ——			
Blanking						— — — / ——	— — —			
Draw		— — — / ——	— — —	— — —	— — —	— — —	— — —	— — —		
Redraw		— — — / ——	— — —	— — —	— — —	— — —	— — —	— — —		
2nd redraw		— — — / ——	— — —	— — —	— — —	— — —	— — —	— — —		
bulging					— — —	— — —	— — —	— — —	— — — / ——	

station individually. So, if the T^2 control chart indicates an out-of-control condition, it means at least one of three draw stations likely has a failure.

(4) In the bulging station, its working range covers from segment S_5 to segment S_9. Segment S_9 is selected as the monitoring segment since it is a critical range to the condition of the bulging station as shown in Fig. 4 and also has the least overlaps with other stations.

4.4 Blanking Station Monitoring and the Interaction Effect Analysis

4.4.1 Blanking Station is a Critical Operation in the Doorknob Process. Among seven operations in the doorknob process, the blanking station is very critical in terms of the following two major reasons: (1) tool lifetime. A faster wear rate and high broken failures of the punch die is generally observed at the blanking station than that at other stations in this doorknob process; (2) influence on the final product quality and on the die working conditions of other stations. The burr defects on the workpiece surface are generated at the blanking station due to the worn blanking die, which can affect not only the final product quality but also the die working conditions of other stations after the blanking station. Therefore, the following detailed discussion for process monitoring will focus on the blanking station, which includes (1) how to implement on-line monitoring of the blanking station based on the press tonnage signals, and (2) how to quantify the interaction effect of blanking die failures on the false alarm rate of other station monitoring.

In order to demonstrate the effectiveness of the proposed methodology, the press tonnage signals with two blanking die conditions (good punch and worn punch) are used in the study. Figure 5 shows the press tonnage signals within the working range of the blanking station. There are sixty samples for each of the good and worn punch conditions respectively.

4.4.2 Blanking Station Monitoring. Based on the discussion in Section 4.3, segment S_6 is selected as the monitoring segment (data index is [100 105]) for the blanking station. The first thirty samples of the press tonnage signals under the good punch condition are used to construct Phase I control limits of the blanking station, in which only the signals at segment S_6 is used. Figure 6 shows the T^2 statistics of those thirty preliminary samples and the Phase I control limits. It can be seen that those preliminary samples are all within the Phase I control limits, which are then used to obtain the estimates of the mean and covariance $\overline{\mathbf{x}}$ and S^{-1} used in the Phase II control chart.

The Phase II control limits and the T^2 statistics of all 120 samples are shown in Fig. 7. From Fig. 7, it can be seen that the statistics T^2 of the first 60 samples under the good punch condition are all in control, while the T^2 statistics of the last 60 samples corresponding to the worn punch conditions are all out of control. Therefore, those abnormal blanking die conditions are detected by using the T^2 control chart at the monitoring segment S_6.

4.4.3 False Alarm Rate Evaluation. According to Eq. (4), the false alarm rate of station j monitoring in the doorknob stamping process can be expressed as

$$\alpha_j = \alpha \cdot p_j(0) + \sum_{i=1}^{2^6-1} \gamma_j(i) p_j(i), \quad (j=1,2,\ldots,7) \qquad (11)$$

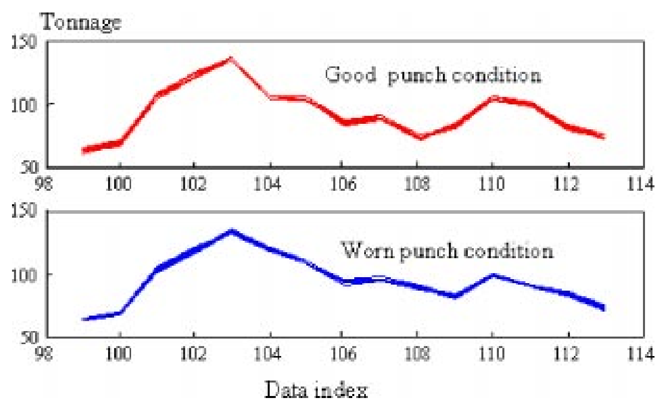

Fig. 5 Press tonnage signals at two different punch conditions

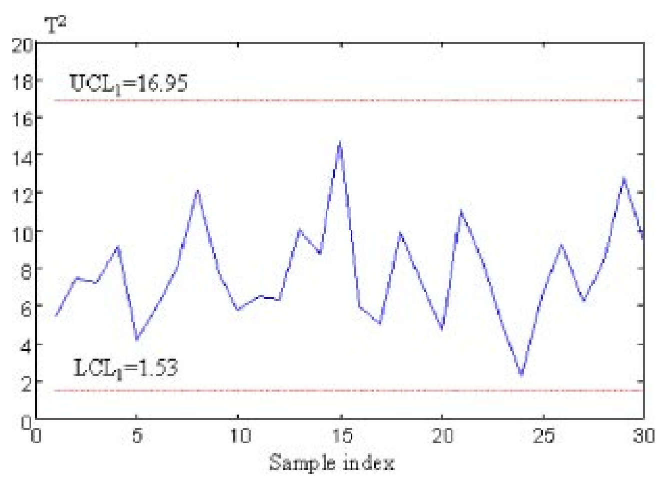

Fig. 6 Phase I control limits to check the preliminary in-control data

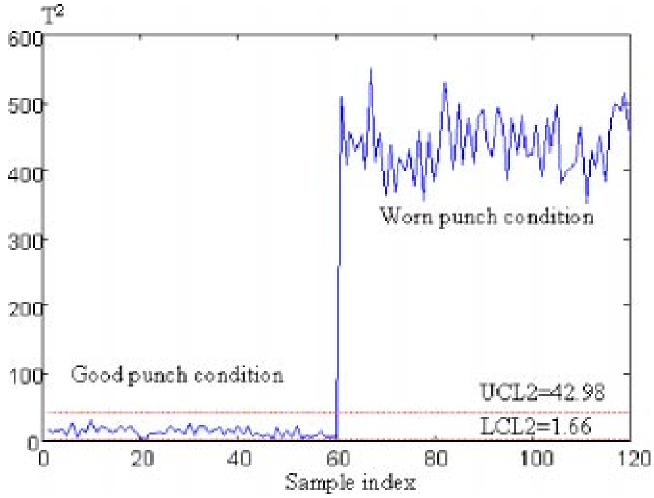

Fig. 7 Phase II control limits to detect the out-of control condition

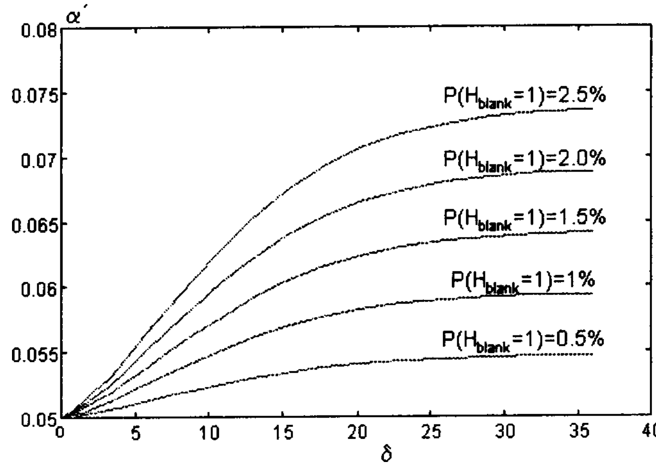

Fig. 8 The false alarm rate of the cutoff station

Eq. (11) considers all potential effects of other six unmonitored stations on the monitoring segment of station *j*.

(a) False alarm rate in the blanking station: Based on the discussion in Section 3.2.3, when the monitored station *j* is the blanking station, Eq. (11) can be simplified by first ignoring the unoverlapping stations of the notch and cutoff stations because the notch station finishes before the blanking station, and the cutoff station starts after the blanking stations. Secondly, although the working range of three draw stations are overlapping with the monitoring segment of the blanking operation, the effect of three draw stations on the blanking station monitoring are also ignorable because the probability of these draw station failures in this doorknob process is very small by comparing with the failure rate of blanking station (about 20 times lower, [15]). Lastly, the effect of bulging station failures on the monitoring segment S_6 is also approximately ignored because most of bulging station failures are due to the wear-out of the rubber-die. The wear of the rubber-die normally affects the tonnage signal at segment S_9 and has little impact on the tonnage signal at segment S_6. In summary, the false alarm rate of the blanking station monitoring is not significantly affected by other station conditions, and thus approximately equal to the initial α specified in the T^2 control chart.

(b) The effect of blanking station failures on the false alarm rate of the cutoff station: From Table 2, it can be seen that the working range of blanking station has no overlap with the monitoring segments of all other stations except for the cutoff station. Therefore, the blanking station failure may only affect the monitoring segment S_7 for the cutoff station monitoring. Based on Eq. (9) and Eq. (11), it is known that the level of the impact is determined by the failure magnitude of the blanking station, the probability of the blanking station failure, and the initial α error in the T^2 control chart at segment S_7.

Based on the similar principle used in the blanking station discussion, it can also show that except for blanking station, the effects of other stations' conditions have little impact on the cutoff station monitoring. Thus, the false alarm rate evaluation for the cutoff station monitoring only needs to consider the effect of the banking station failure. A generic relationship to show the effect of the blanking station failure on the false alarm rate of the cutoff station monitoring is given in Fig. 8. The horizontal axis in Fig. 8 is the non-centranality distance δ representing the transformed magnitude of the blanking station failures. The vertical axis in Fig. 8 is the true false alarm rate in monitoring of the cutoff station, in which the interaction effect of the blanking station failures on the monitoring segment of the cutoff station is considered. From the figure, it can be seen that the true false alarm rate of the cutoff station monitoring (α') is the same as the Type I error α=5% specified in the T^2 control chart if the blanking station is under in-control normal condition (i.e. δ=0). However, the false alarm rate will increase as the wear of the blanking station increases (i.e., δ increases). As the blanking station has a significant wear (i.e., δ>35), the false alarm rate will achieve its upper boundary. This is because that the cutoff station would always show an out of control false alarm $[\gamma_{cutoff}(H_{blank}=1)=1]$ due to the blanking station failure with δ>35. In this situation, the impact of the blanking station failure on the cutoff station monitoring is purely dependent on the probability of the blanking station failure, that is, $\alpha' = \alpha \cdot [1 - P(H_{blank}=1)] + P(H_{blank}=1)$. This upper boundary can be used to evaluate the worst case of the false alarm rate for the selected monitoring segment. In this case study, the false alarm rate of the cutoff station monitoring using segment S_7 will be 0.054 under the worn punch condition in Fig. 5, where $\alpha_0 = 0.05$ and $P(H_{blank}=1) = 0.01$ are used.

5 Conclusions

A new method is developed for individual station condition monitoring in multiple operation stamping processes by using the available press tonnage sensors. In this paper, individual station monitoring is conducted by constructing a Hotelling T^2 control chart on the partitioned monitoring segment. The interaction influence of the overlapping stations on the monitoring segment is investigated, which is reflected by an increased false alarm rate by comparing with the Type I error pre-specified in the Hotelling T^2 control chart. The assessment of whether the monitoring segment can be used for individual station monitoring is dependent on whether the increased false alarm rate is acceptable for a given application. In the evaluation analysis of the false alarm rate, it shows that the analysis can be significantly simplified by removing those stations which satisfy one of the following three conditions: (a) their working ranges are not overlapping with the monitored station at the monitoring segment; (b) their failure probability is close to zero; (c) their failures cause little change on the press tonnage signals within the monitoring segment. To illustrate implementation procedure and the effectiveness of the methodology, a doorknob stamping process is used as a real-world example in the paper.

It is worth pointing out even though a monitoring segment may not exist for a particular single station monitoring in some applications, the proposed method of using segmental signal monitoring is still more appealing for fault diagnosis. In this case, the compound monitoring results can limit the search of failure stations to a few stations compounding at the monitoring segment rather than all stations in the process. Also, it can provide a systematic judgment to determine in-die sensor locations where they are really needed.

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Appendix

Proof of T^2 Statistics in Eq. (8) Following a Noncentral *F* Distribution

If a normal distribution is assumed, the distribution of $\mathbf{x}_i-\overline{\mathbf{x}}$ in T^2 statistic is:

$$\mathbf{x}_i-\overline{\mathbf{x}}\sim \mathbf{N}\left(\boldsymbol{\mu}_f-\boldsymbol{\mu},\frac{m+1}{m}\boldsymbol{\Sigma}\right) \tag{12}$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\mu}_f$ are the signal mean of the monitoring segment of station i under the condition of event B_0 and $B_i\,(i\neq 0)$ respectively. $\boldsymbol{\mu}$ and $\boldsymbol{\mu}_f$ can be estimated by $\overline{\mathbf{x}}$ and $\overline{\mathbf{x}}_f$ from the samples collected under the conditions of event B_0 and $B_i\,(i\neq 0)$ respectively. Based on Eq. (12), a new variable $\mathbf{y}_i$ is defined as $\mathbf{y}_i=\sqrt{m/m+1}(\mathbf{x}_i-\overline{\mathbf{x}})$, and its distribution is:

$$\mathbf{y}_i=\sqrt{\frac{m}{m+1}}(\mathbf{x}_i-\overline{\mathbf{x}})\sim \mathbf{N}(\boldsymbol{\mu}_y,\boldsymbol{\Sigma}) \tag{13}$$

where $\boldsymbol{\mu}_y=\sqrt{m/m+1}(\boldsymbol{\mu}_f-\boldsymbol{\mu})$. Therefore, the statistics T^2 in Eq. (8) can be rewritten as:

$$T^2=\frac{m+1}{m}\mathbf{y}_i^T\mathbf{S}^{-1}\mathbf{y}_i \tag{14}$$

Based on the non-central Chi-square distribution, it is known that:

$$\mathbf{y}_i^T\Sigma^{-1}\mathbf{y}_i\sim\chi^2_{p,\delta} \tag{15}$$

where $\delta=\boldsymbol{\mu}_y^T\boldsymbol{\Sigma}^{-1}\boldsymbol{\mu}_y$, and $\chi^2_{p,\delta}$ is the noncentral Chi-square distribution with the p degrees of freedom and the noncentranality δ. It has been proven that by Seber [19]:

$$\frac{\mathbf{y}_i^T\Sigma^{-1}\mathbf{y}_i}{\mathbf{y}_i^T\mathbf{W}^{-1}\mathbf{y}_i}\sim\chi^2_{m-1-p+1}, \tag{16}$$

where $\mathbf{W}=(m-1)\mathbf{S}\sim\mathbf{W}_p(m-1,\Sigma)$, and $\mathbf{W}_p(m-1,\Sigma)$ is the Wishart distribution.

Since $\mathbf{y}_i^T\Sigma^{-1}\mathbf{y}_i/\mathbf{y}_i^T\mathbf{W}^{-1}\mathbf{y}_i$ is independent of $\mathbf{y}_i$ [19], the distribution of T^2 can be derived as follows:

$$T^2=\frac{m+1}{m}y_i^TS^{-1}y_i=\frac{(m+1)(m-1)}{m}\cdot\frac{y_i^T\Sigma^{-1}y_i}{\left(\frac{y_i^T\Sigma^{-1}y_i}{y_i^TW^{-1}y_i}\right)}$$
$$\sim\frac{(m+1)(m-1)}{m}\cdot\frac{\chi^2_{p,\delta}}{\chi^2_{m-p}}\sim\frac{(m+1)(m-1)p}{m(m-p)}\cdot F(p,m-p,\delta) \tag{17}$$

thus, $T^2/K\sim F(p,m-p,\delta)$, where $K=(m+1)(m-1)p/m(m-p)$.

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