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Using stamping punch force variation for the identification of changes in lubrication and wear mechanism

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Abstract. The growth in use of Advanced High Strength Steels in the automotive industry for light-weighting and safety has increased the rates of tool wear in sheet metal stamping. This is an issue that adds significant costs to production in terms of manual inspection and part refinishing. To reduce these costs, a tool condition monitoring system is required and a firm understanding of process signal variation must form the foundation for any such monitoring system. Punch force is a stamping process signal that is widely collected by industrial presses and has been linked closely to part quality and tool condition, making it an ideal candidate as a tool condition monitoring signal. In this preliminary investigation, the variation of punch force due to different lubrication conditions and progressive wear are examined. Linking specific punch force signature changes to developing lubrication and wear events is valuable for die wear and stamping condition monitoring. A series of semi-industrial channel forming trials were conducted under different lubrication regimes and progressive die wear. Punch force signatures were captured for each part and Principal Component Analysis (PCA) was applied to determine the key Principal Components of the signature data sets. These Principal Components were linked to the evolution of friction conditions over the course of the stroke for the different lubrication regimes and mechanism of galling wear. As a result, variation in punch force signatures were correlated to the current mechanism of wear dominant on the formed part; either abrasion or adhesion, and to changes in lubrication mechanism. The outcomes of this study provide important insights into punch force signature variation, that will provide a foundation for future work into the development of die wear and lubrication monitoring systems for sheet metal stamping.

1. Introduction

Die and tooling wear in sheet metal forming is a continuing issue in automotive manufacture, particularly with the increasing use of higher strength steels. Forming these stronger steels has required higher forces which has accelerated tool wear rates. This issue is exacerbated when coupled with the push for industry to move away from traditional stamping lubricants to reduced lubrication and unlubricated stamping for environmental and economic reasons [1]. As a result, research into and the development of real-time process monitoring to assess tool condition and lubrication has become



increasingly important. Tonnage or punch force is a useful and easy to collect source of process information. Punch force signals are closely linked to the state of friction in the process [2] and many industrial presses are equipped with tonnage sensor equipment for overload protection. Punch force is a function of friction at the interface of the press tooling and parts in the stamping system [3]. Friction modifiers, such as lubricants and tooling wear, will influence punch force over the course of a stroke. Investigating variation of load curves for parts or punch force signatures reveals information about the friction state of the process, which in turn can assist with understanding wear progression and lubrication variation. Results for this investigation will provide a foundation for the development of force based real time tool wear and lubrication monitoring in sheet metal stamping.

Mizuno and Kataoka [4] investigated changing lubrication conditions in deep drawing and found that conditions and mechanisms change throughout the forming process. Specifically, lubricant oil film thickness was found to vary at different contact locations and typically decreased as the forming progressed causing the mechanism to change from boundary to mixed, leading to an increasing friction. An increase in punch force during the stroke can be expected with the change in lubrication regime seen with fluid lubricants. Dry-film lubrication regimes can maintain film thickness [5] and so will potentially maintain a single lubrication regime over the course of the stroke, hence maintaining consistent friction and punch force levels.

Gåård et al. [6] investigated galling wear mechanisms and surface damage on deep drawing dies and sheet steel. They demonstrated the progression of galling wear damage of sheet material from abrasive scratching to severe adhesive damage. The typical appearance of the abrasive stage of galling is regular parallel scratching in the surface, while the adhesive stage of galling exhibits an uneven surface with numerous raised protrusions or lips. This adhesive damage corresponded to a rapid increase in measured friction between the tool and sheet material. Progression of galling wear stages from abrasive to adhesive cause an increase in the contact friction between part and press tooling, and this should be reflected in the punch force signature as an increase in force levels.

In this study, an initial investigation was conducted into the effects of dynamic friction changes due to lubrication and wear mechanism changes on punch force signatures for the purposes of improving force-based process monitoring. Two experiments have been conducted focusing on punch force signature variation due to lubrication changes and die wear progression. PCA has been used to identify the major forms of punch force signature shape variation and to track how the punch force signatures vary from part to part. Previous work [7] has shown a consistent increase in punch force over the course of a stroke under normal fluid lubrication regimes. However, in unlubricated trials, punch force plateaued and remained comparatively consistent over the course of the stroke. In the first experiment this was investigated further, by testing fluid and solid film lubrication regimes to determine if increases in punch force observed with fluid lubricants are caused by changes in the lubrication regime mid-stroke. The previous work [7] also showed that punch force variation can be used to detect changes in the severity level of galling wear. In the second experiment, an investigation is conducted to determine if variation in punch force signature can be linked to galling wear mechanism changes as identified using visual assessment of formed parts.

2. Experimental methods

2.1. Deep drawing stamping trials

Experimental channel forming trials were conducted on a single action mechanical press reported by Pereira et al. [8], figure 1, equipped with an automated sheet feeder and straightener. Press geometry and material selection were designed to represent a wear prone automotive deep drawing operation. The main geometry and press process variables are summarised in table 1. The blank material was High-Strength Low-Alloy sheet steel (XtraForm 300), yield strength of 300MPa and tensile strength of 440MPa. The press operated with a ram speed of approximately 300 mm/s at the beginning of the forming operation and decelerated to 0 mm/s at the end of the stroke. The blank holder force applied by the gas springs was an average of 28kN. As the ram speed and blank holder force development over the

course of each stroke were consistent throughout the experimental trials they did not influence punch force signature variation between parts. A load cell was located in the base of the stationary punch and punch force signals were recorded at 1000Hz, providing 300 punch force data value for each part. A range of 7 lubrication regimes were used in the lubrication experiment, including unlubricated, various fluid lubricants and dry-film lubricants, table 2. All fluid lubricants were brush applied by hand to the blank material. The dry Polytetrafluoroethylene (PTFE) coating was evenly applied by hand with aerosol can, and finally PTFE sheets were positioned above and below blank material prior to forming. Die radius inserts used in the lubrication trials were made of plasma nitrided and TiCN Physical Vapour Deposition coated AISI D2 tool steel so as to eliminate tool wear as a variable. For these lubricant trials all other parameters were held constant. The wear experiment involved forming 150 channel parts with AISI D2 tool steel die radius inserts, that were allowed to wear over the course of the experiment. The die radius inserts used for the wear experiment exhibited galling wear on both inserts and had previously formed parts under the same experimental conditions. All other parameters in the wear experiment were held constant.

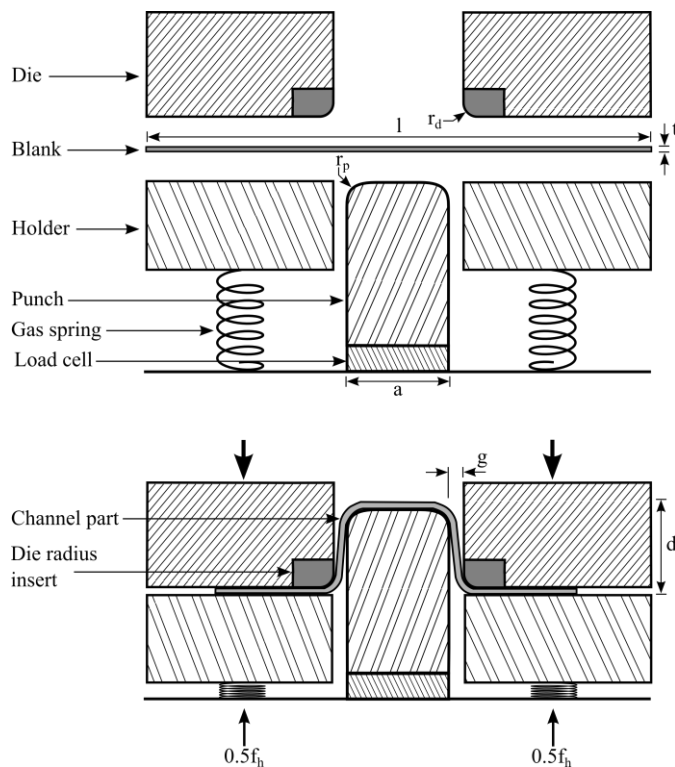


Figure 1. Channel forming press schematic.

Table 1. Process variables for channel forming operation

Punch width, a	30mm
Draw depth, d	40mm
Average blank holder force, f_h	28kN
Blank length, l	150mm
Die corner radius, r_d	5mm
Punch corner radius, r_p	5mm
Blank thickness, t	1.8mm
Blank width, w	26mm
Punch to die gap, g	2.3mm

Table 2. Lubrication details

Lubricant Type	Details	Number of parts
Mill Oil	Quaker Ferrocote 366 K2 Anti-corrosive mill oil	38
Ionic liquid	Ionic liquid ($P_{6,6,6,1,4}$ BEHP) 3% by weight in mineral oil [9]	50
Mineral Oil	Grade II mineral oil [9]	50
Drawing lubricant	Fuchs Renoform MP63 l	50
Dry PTFE coating	WD-40 Anti-friction Dry PTFE lubricant	50
PTFE sheet	PTFE coated fibreglass fabric	50

2.2. Principal Component Analysis

PCA is an image recognition technique that has been used for the analysis of punch force signatures for detection of part failure [10] and process variation [11]. The PCA method isolates the Principal Components, major forms of shape variation, in a training set of punch force signatures. The process can then be used to reduce any punch force signature of the same length to a number of coefficients, b -values, that characterise the signature shape in terms of the Principal Components or form of shape variation. The PCA method is applied such that a punch force signature can be describe by the following:

$$\hat{X}_i = \bar{X} + \mathbf{P}\mathbf{b}_i \quad (1)$$

Where \bar{X} represents the mean vector of the punch force signature training set, and \mathbf{P} is the matrix of significant eigenvectors determined for the covariance matrix of the training set matrix. The vector \mathbf{b}_i is the vector of weighted coefficients or b -values that describe the punch force signature \hat{X}_i in terms of each Principal Component. Rearranging equation (1) \mathbf{b}_i can then be determined:

$$\mathbf{b}_i = \mathbf{P}^+(\hat{X}_i - \bar{X}) \quad (2)$$

Where \mathbf{P}^+ is the pseudo inverse of the \mathbf{P} . By calculating b -values for each punch force signature, it is possible to track the changes in specific form signature shape change from part to part.

2.3. Visual assessment of wear trial parts

Photographs of both sidewalls for each part formed in the wear trials were taken for visual assessment of galling wear damage. Sidewalls were named according to the corresponding die insert (Die 1 and Die 2) and part number. For ease of assessment of part sidewalls, the photographs were uniformly subdivided into 8 sections, with early and late stroke regions labelled A and B , respectively, and the width of part divided into 4 even sections, figure 2. Visual assessment was conducted by comparing damage progression on sidewalls of the same die between consecutively formed parts. Specific attention was given to the amount and severity of adhesive wear damage observed in the galling tracks.

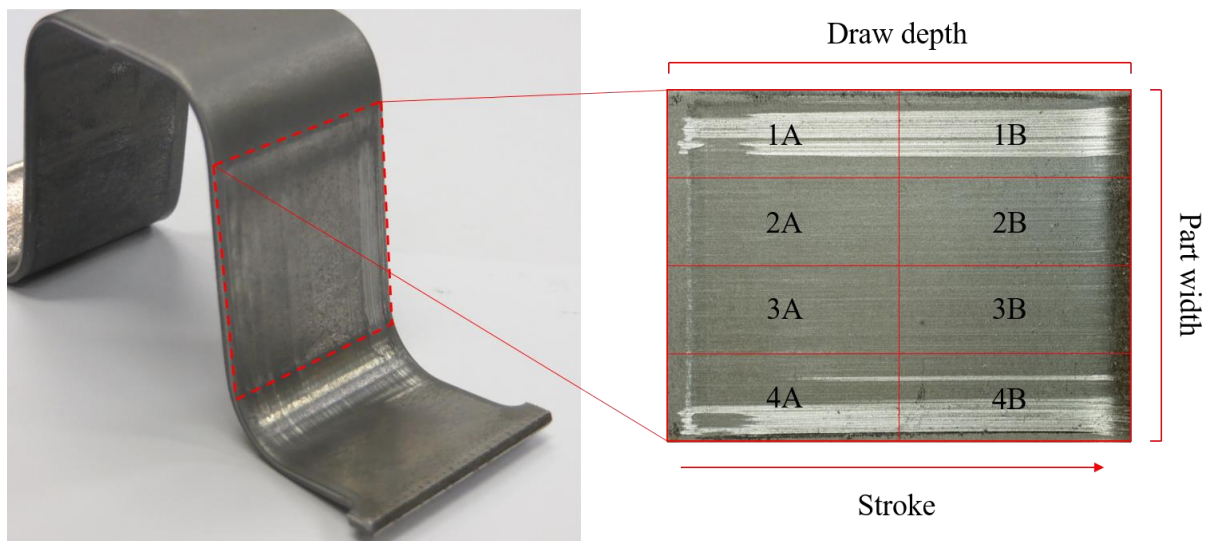


Figure 2. Regions and labels of part sidewall visual assessment.

3. Results

Average punch force signatures were calculated for each of the lubrication trials to give a representative signature shape for each trial, figure 3 *a* and *b*. Fluid lubrication regimes demonstrate the late-stroke force increase, while the dry-film lubrication in the form of the dry PTFE coating and the PTFE sheets exhibited stable or decreasing punch force, respectively.

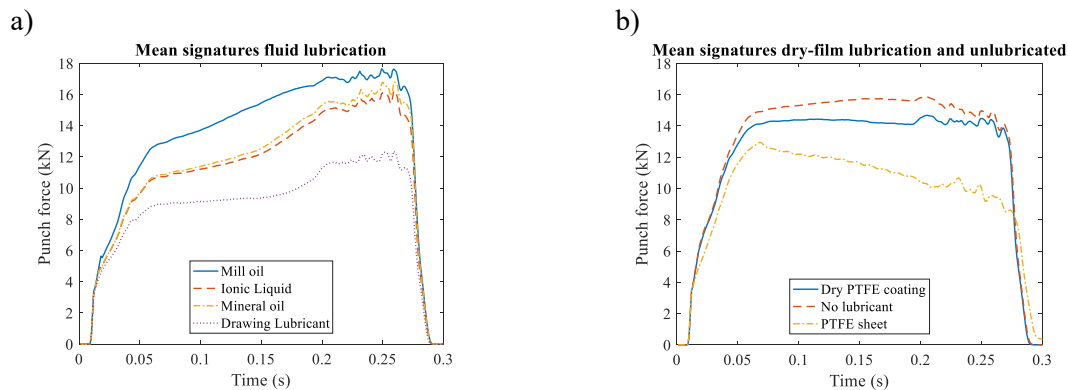


Figure 3. Punch force signatures for lubrication studies. a) Mean punch force signatures for fluid lubrication. b) Mean punch force signatures for un lubricated and dry-film lubrication.

The lubrication punch force signatures were used to develop a training set for PCA. Representative signature shapes for the first two Principal Components can be seen in figure 4 *a* and *b*; where the first Principal Component represents variation in the overall level of force in the signature, and the second Principal Component represents slope of the signature plateau or the rate of increase or decrease in force over the course of the stroke. These Principal Components represent a combined 97.6% of total signature variation.

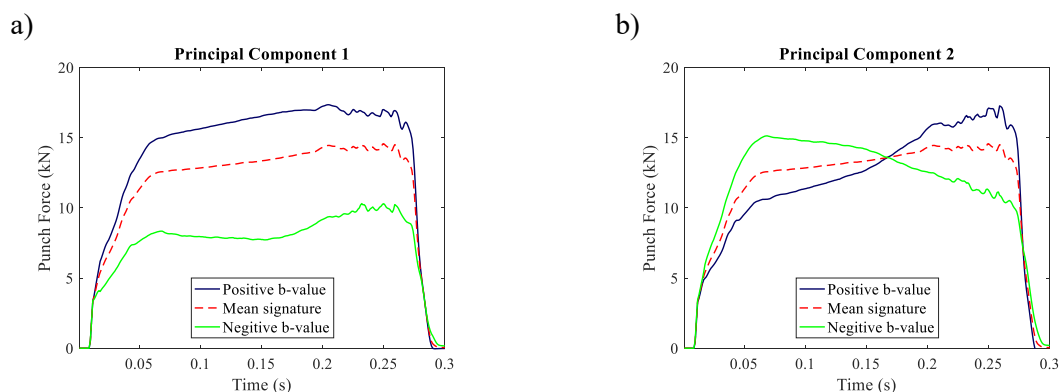


Figure 4. PCA main Principal Component representations. a) First Principal Component signature shapes. b) Second Principal Component signature shapes.

Each punch force signature can be represented as b -values, according to equation (2), that describe the signature in terms of each Principal Component. Here, the positive b -values for Principal Component 1 and Principal Component 2 represent an overall increase in punch force and a late stroke increase in punch force, respectively. The b -values for each of the punch force signatures collected in the lubrication experiment were then determined for the two selected Principal Components. Figure 5 shows the difference in b_2 values for dry and fluid lubrication regimes, highlighting the late stroke increase in force that is distinct for the fluid lubricants, with all fluid lubricants tested having positive b_2 values. Positive

b_2 values represent an increase in force over the course of the stroke and therefore a progressive increase in friction, suggesting that the lubrication mechanism changes over the course of the stroke. Negative b_2 values, on the contrary, represent near steady-state or decreasing force over the course of the stroke and therefore near steady-state or decreasing friction conditions. The no-lubricant and dry PTFE coating trial signatures have negative b_2 values and the mean signatures from each trial have near steady-state punch force over the course of the stroke, suggesting that the lubrication mechanism remains consistent for these regimes. The mean PTFE sheet signature and b_2 values suggest decreasing friction over the course of the stroke.

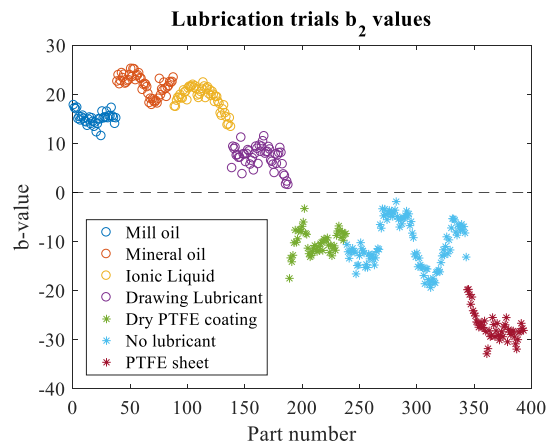


Figure 5. b_2 values for lubricant trials.

The Principal Components calculated for the lubricant experiment punch force signatures captured the signature shape variation useful for tracking galling wear mechanism change. In particular, Principal Component 2 (figure 4 *b*) captures variation in the rate of increase or decrease in force over the course of the stroke which provides the necessary information to detect mid-stroke changes in galling wear mechanism. The b_2 values for the wear experiment punch force signatures were calculated and consecutively formed parts with large differences in b_2 values were visually assessed and compared. The focus of this comparison was adhesive wear damage late in the stroke that would drive an increase in late stroke punch force. Comparing consecutively formed parts ensured that the quantity and number of galling wear sites remained relatively constant so that the galling mechanism was the only variable. This initial visual assessment and comparison of a number of selected parts has shown that b_2 value increases correspond to an increase in adhesive wear damage on the late-stroke component of the galling tracks. With increasing b_2 values an increase in adhesive damage area towards the end of the stroke is expected to drive the increased friction later in the stroke. An example comparison of adjacent wear experiment parts with a large change in b_2 value is seen in figure 6. An increase in adhesive wear damage can be observed on part 1632 when compared to part 1634, in the 1B and 4B regions in particular, both late stroke regions.

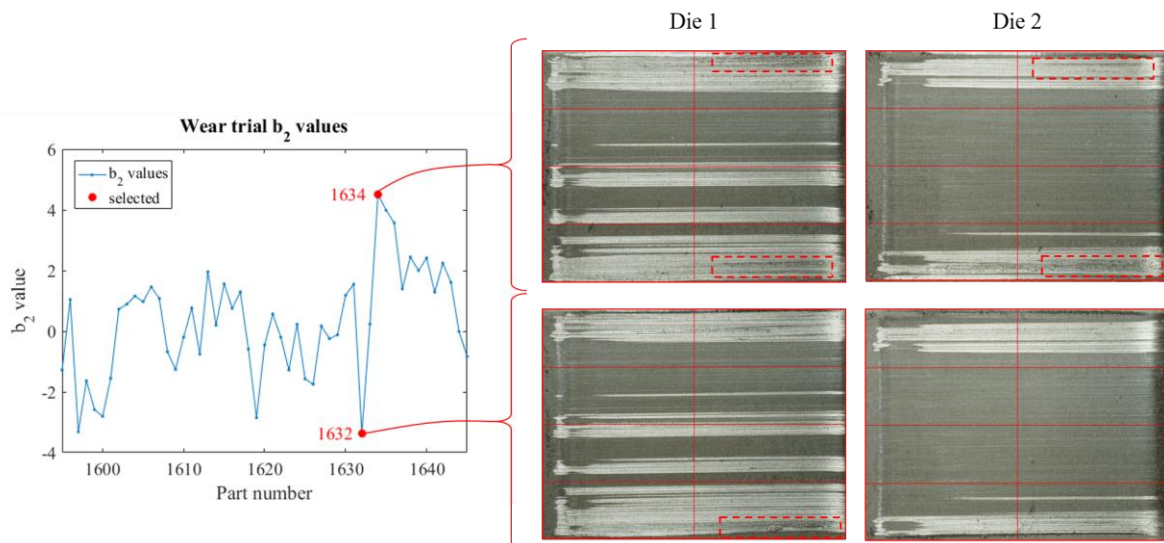


Figure 6. Depiction of b_2 values for each part in the wear trial (left). Part sidewall photos of example parts are shown (right) that highlight the increased area of adhesive damage late in the stroke on part 1634.

4. Discussion

In this study two experiments were conducted to evaluate the effects of dynamic friction changes on punch force signatures. In the first experiment, different lubricants were tested and showed that variation in punch force signature observed between trials is linked to mid-stroke lubrication mechanism changes. In the second experiment, the amount and location of galling wear damage on parts was compared to variation in the punch force signatures and a link between galling wear mechanism change and punch force variation was found.

The results of the lubrication experiment suggest that PCA of punch force signatures shape can be used to monitor lubrication mechanism changes over the course of the stroke for fluid lubrication. By examining the b_2 values and mean signatures for the lubrication experiment (figure 5 and figure 3), it is clear that force and friction increase during the stroke for fluid lubricants, suggesting that a change in lubrication mechanism occurs when using fluid lubrication. This is not observed for unlubricated and dry-film lubricants. The mean signature shapes (figure 3 *a* and *b*) for different lubrication regimes demonstrate the distinction between fluid lubricated, dry-film lubricated, and unlubricated punch force signatures, and supports the hypothesis of fluid lubricant film reduction and mechanism change over the course of the stroke. The second Principal Component (figure 4 *b*) characterises the dynamic change in friction over the course of the stroke. The corresponding b_2 value plot (figure 5) for the lubrication experiment demonstrates that PCA of punch force signatures can isolate the variation that comes with fluid lubrication thinning over the course of the stroke. Lubricant viscosity, surface roughness, blank holder force and ram speed all play a role in this friction development [12], however, viscosity of individual lubricants, surface roughness of the blank material, and the effect of blank holder force and ram speed change are assumed to be consistent throughout the experiments. As a result, these parameters do not contribute to the punch force variation assessed in the study. Interestingly, the deceleration of ram speed towards the end of the stroke that occurs in the conducted experiments supports the conclusion that punch force signatures can detect lubrication mechanism change. Andreasen et al. [13] found that lower sliding speeds in Bending Under Tension tests led to significant friction stresses and lubrication film breakdown, so an increase in punch force should be expected as the ram speed decreases. Such an increase in the punch force signatures is only observed for the fluid lubrication trials, suggesting that lubrication film breakdown is occurring. Finally, a decrease in punch force over the course of the stroke was observed in punch force signatures collected in the PTFE sheet trial, figure 3 *b*. As the type of

lubricant was the only press parameter varied in the lubrication trials, the decreasing force and friction seen with PTFE sheet trial are assumed to be driven by the properties and behaviour of the PTFE sheet material. However, further investigation is needed to fully explain these observations.

The results of the wear experiment suggest that specific forms of punch force signature variation can be used to detect changes in mechanism and amount of galling wear present on the formed sheet metal parts. The PCA and b -value method allows for this variation in punch force signature shape to be determined and monitored. Changes in b -values determined for the wear trial correlate with visual observations of increased quantities of galling wear adhesive damage localised at the end-of-stroke section of the part. The increased b_2 values assessed in the wear data correspond to a higher than average positive slope of the punch force plateau and an increase in area of adhesive wear damage in the galling track in the late-stroke region of the sidewalls. These observations indicate that localised increases in adhesive damage, a result of galling wear mechanism change, can be detected in punch force signature shape variation captured by using PCA and displayed by using b -values. The visual assessment results are qualitative in nature and further data collection is required to develop a quantifiable link between galling wear progression and wear stage, but the general trend between increased adhesive damage area and high b_2 values has been observed in this study.

5. Conclusion

The presented results demonstrate that variation in punch force signatures captured using PCA can be used to detect dynamic changes in friction caused by galling wear mechanism change and change in lubrication. This provides a foundation for further work into development of a real-time tool wear and lubrication monitoring system for the stamping industry that utilises PCA analysis of punch force. Such a real-time tool wear and lubrication monitoring system would allow for the stamping industry to monitor and detect the onset and development of tooling wear and lubrication changes.

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