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Developing smart multi-sensor monitoring for tool wear in stamping process

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Abstract: Tool wear and galling are of significant concern in the automotive stamping industry, due to the increase in use of higher strength sheet steels in automotive structures and reduced lubrication during stamping production. There are many methods explored in the literature and applied in industry to combat wear in stamping, including new die materials and coatings, alternative lubrication systems and better predictive models. However, smart condition monitoring will continue to be relevant in conjunction with these methods because it can provide further opportunities for production quality and cost improvements, despite the advancements of these other methods. This paper explores the use of multiple sensors and multiple signal processing techniques, aimed at developing a smart multi-sensor method to monitor galling wear. The three main sensors and corresponding signal processing techniques examined are: (i) measurement of punch force signatures analyzed via Principal Component Analysis (PCA); (ii) acoustic emissions signals measured via wideband sensors and examined using time and frequency domain features; (iii) measurement of audio signals in the audible frequency range analyzed via blind signal separation techniques. For all techniques, a semi-industrial stamping test was used to provide realistic production-type conditions, albeit with accelerated wear rates. The relationship between the key outputs from the three sensor/analysis methods were directly compared to a new quantitative measure of galling wear severity. Based on these results, it was observed that a multi-sensor approach for wear condition monitoring provides an opportunity for the development of a smart monitoring tool that can actively track the progression of wear.

Keywords: Tool wear; Galling; Smart monitoring; Condition-based maintenance.

1. Introduction

Galling wear which is a type of adhesive wear mechanism that is commonly observed on the sheet metal stamping tool and leads to premature failure [1]. Due to galling wear, protrusion of transferred material on the stamping tool can become work hardened and result in severe scratches on the sheet surface resulting in poor part quality [2]. As the galling wear in the sheet metal stamping process may be dependent on multiple process parameters, a suitable fault detection method is required to identify galling wear development at the initial stages to avoid poor part quality and unscheduled maintenance [3]. Extensive studies have been conducted in the literature to monitor tool wear using different fault diagnosis technique. For example, force sensors have been used to study part failures, identify change in process settings and contact pressure distribution on the stamping tool [4-5]. Attempts have also been made to monitor onset of galling wear on the stamping tool using force sensor [6]. However, as the force sensors are of high cost, susceptible to noise and require large installation space, its wider use is restricted [7-8]. Numerous attempts have also been made to study different faults in the stamping process



using strain sensors. The fault diagnosis of stamping tool using strain sensor was mainly used to identify abnormal and normal conditions of the stamping tool [9-11]. According to Ge et al. [12], the strain sensor cannot capture the dynamic characteristics of the stamping process. Strain sensors also need to be mounted on the tool or sheet which may hinder the metal stamping operations. As the stamping process works on the principle of energy transformation, Ge et al. [12] used accelerometer to perform fault diagnosis of the stamping process. The stamping process is typically non-stationary; therefore, it typically contains noise from unwanted sources. This situation may require the use of a secondary signal processing technique to filter the noise. This is one of the primary reasons that prevents wider usage of accelerometer for fault diagnosis. Compared to the other type of sensors, acoustic emission (AE) does not require a secondary signal processing technique to filter noise because its frequency range is much higher than compared to machine noise. Skåre et al. [15] and Shanbhag et al. [16-17] have successfully used AE to study wear progression of the stamping tool. Similar to strain sensors, AE sensors need to be mounted on the tool or sheet for fault diagnosis. Compared to other sensors, audio sensors have the capability to meet the demand of non-disruptive operations as direct contact with the tool or sheet is not required. However, as it is highly sensitive to the background noise, its wider usage is restricted. Ubhayaratne et al. [18] developed a semi-blind signal separation technique to recover stamping signal from the background noise. This recovered audio stamping signal was further employed to study wear progression of the stamping tool.

From the literature it is evident that, the sensors used for fault diagnosis of a stamping tool have certain advantages and disadvantages. Therefore, there is a need to perform a smart monitoring study of stamping tool using different sensors to identify a suitable sensor that can be used to actively track galling development on stamping tool. As force, acoustic emission and audio sensors have been successfully used to monitor galling wear progression on the stamping tool, therefore in this study an attempt will made to study galling wear development on the stamping tool under the same experimental stamping conditions.

Therefore, to perform the smart monitoring of stamping tool, a series of tests were conducted using accelerated semi-industrial stamping wear tests. Firstly, smart sensor monitoring was performed using force and audio sensor for the un-worn and worn die, using a material combination of D2 steel for the tool and XF-300 for the sheet material. Using the same material combination and experimental conditions, the semi-industrial stamping tests were repeated using AE sensors. The features from the sensor data were correlated with the profilometry wear measurement feature maximum depth to study the wear progression.

2. Experimental details and methodology

2.1. Stamping test details.

The stamping tests were performed under accelerated conditions using a semi-industrial stamping setup. This stamping setup used in this study employs a progressive die that is capable of performing clamping, piercing, stamping and trimming operations in a single cycle. The detailed working of semi-industrial stamping setup is explained in the work done by Ubhayaratne et al. [18]. As shown in Figure 1, channel shaped parts were produced from the stamping tooling. The removable die inserts used in the stamping operation were made from AISI D2 steel, which was through hardened to 55 HRC and precision ground to achieve accurate die radius profile shape. The blank material used in this study is a high strength low alloy steel (XF-300) with a thickness of 1.8 mm. The yield strength and ultimate strength of the blank material in the rolling direction are 321 MPa and 485 MPa, as determined from uniaxial tensile tests. The XF-300 sheet metal coil was fed automatically in the stamping setup via an un-coiler and coil straightener. The stamping tests were performed under un-lubricated condition and the process parameters used in this study were selected to make the die prone to wear within few hundred parts. The process parameters were kept constant throughout the study and are summarised in Table 1. During the test, every fifth part was visually inspected to check the severity of wear on the wall of stamped parts. The stamping tests were performed twice. The first set of stamping tests were performed using audio

and force sensors. The second set of stamping tests were performed using AE sensors. For both the stamping experiments, tests were stopped after stamping 600 parts i.e. when the die was completely worn.

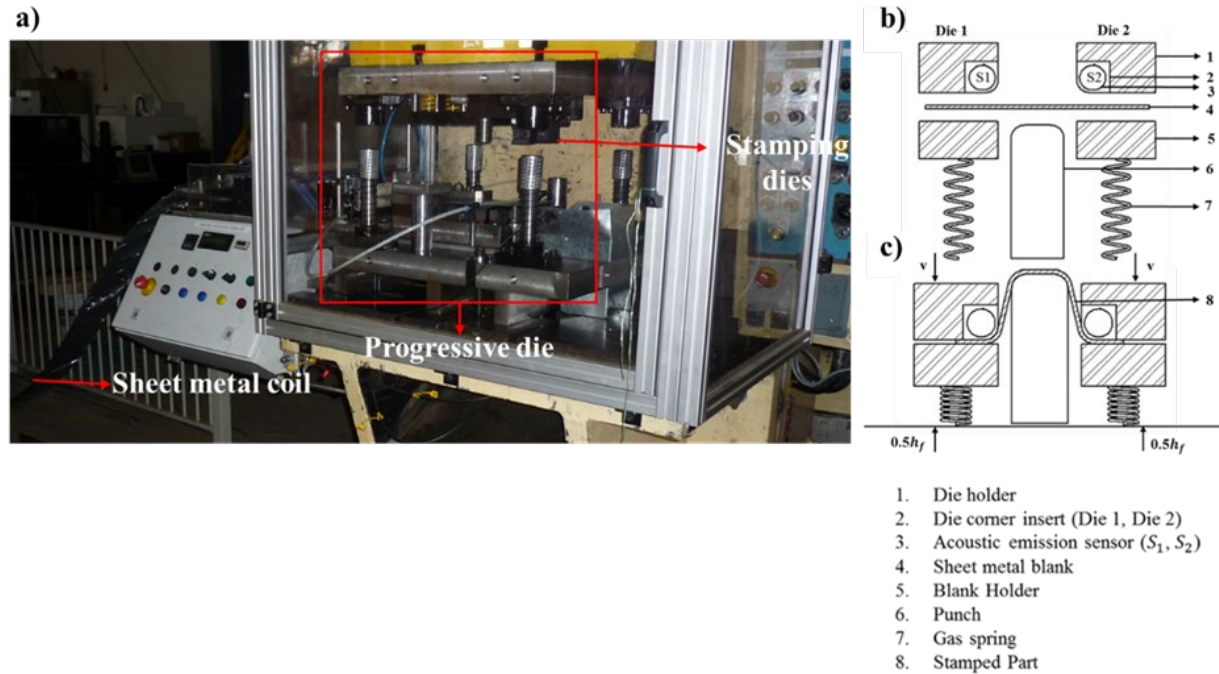


Figure 1. a) Stamping setup. Schematic view of stamping setup b) before stamping c) after stamping.

Table 1. Experimental details for stamping and scratch test.

Lubrication	Dry
Punch width	30 mm
Die to punch gap	2.35 mm
Die corner radius	5 mm
Punch radius	5 mm
Blank size ($L \times W \times t$)	150 × 26 × 1.6 mm
Draw depth	40 mm
Average blank holder force (h_f)	28 kN
Press stroke rate	32 strokes per minute
Number of parts formed	600

2.2. Profilometry study

The side wall of the collected stamped parts was examined using an optical profilometer to understand the tool wear behaviour. In this study, only the wear behaviour on wall of one side of the stamped part is discussed. The selection of stamped parts for the surface examination was based on the visual inspection of wear on the wall of stamped parts. The objective magnification of 5X and scan area of 23X5 mm was maintained constant throughout the profilometry study. As the side walls of the stamped parts were not perfectly flat, a plane feature available in the profilometer software [19] was applied to remove tilt and curvature. Figure 2 represents the methodology adopted for surface examination of the stamped parts using optical profilometer. As shown in Figure 2 c), after the scan of stamped part is completed, a single 2D surface profile of width 50 μm (For stamping test with audio and force) and 5 μm (For stamping test with AE) was obtained at the centreline and maximum depth of the surface profile

was measured. To show repeatability, a normalised maximum depth wear measurement feature was used to correlate features from the sensors (Force, audio and AE).

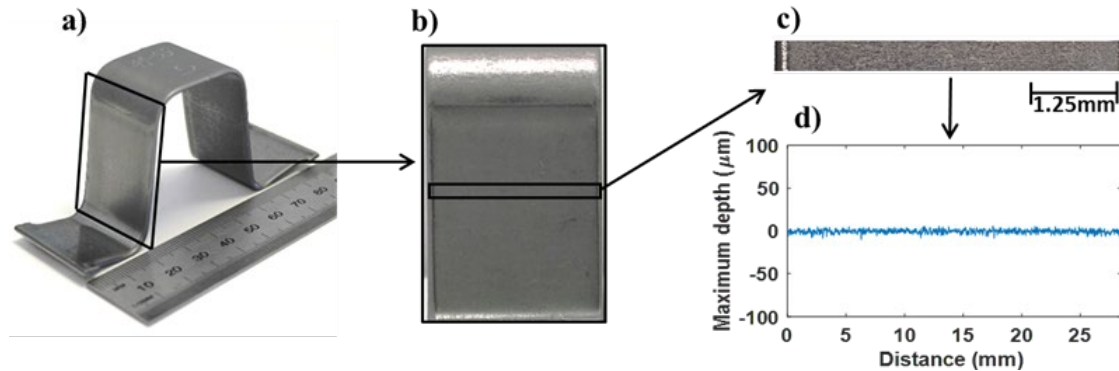


Figure 2: (a) An example of a stamped part and (b) a photograph of the stamped part sidewall in contact with stamping die showing the approximate area measured using optical profilometry (c) profilometer image and (d) 2D surface profile

2.3. Data acquisition details

In this study, the punch force signature was recorded for each stamping tests using Kistler piezoelectric load washer (9041A). This load washer was placed at the base of the stamping punch. The data acquisition of force signature was performed at 1000 Hz using a National instruments data acquisition setup and National instruments signal express software.

In this study, 1 audio sensor (microphone) was used to study the tool wear behaviour. This audio sensor was placed on the upper plate of the tooling, i.e. close to the stamping dies. The data acquisition of audio sensor was performed at 12 kHz frequency. The audio sensor was connected to the National instruments USB-6009 data acquisition system. Detailed description of the data acquisition setup used for audio data recording and application of semi-blind signal extraction technique to separate the audio data of only the stamping signal can be found in the work done by Ubhayaratne et al. [18].

As shown in Figure 1, the AE wideband sensors were clamped to the die inserts using a magnetic clamp. A small amount of ultrasonic couplant was applied to the face of AE sensor before mounting the magnetic clamp on the die inserts. The AE sensors were connected to National instruments data acquisition system (PXIe-1078) via a high-speed digitiser and an AE amplifier with a gain of 40 dB. The AE data acquisition was performed for each test with a frequency of 2 MHz. Stamping AE signal was segregated from different forming operation (Clamping, piercing and trimming) based on the timing of forming process.

The stamping test recorded data using force, audio and AE was subsequently isolated for further processing and analysis in MATLAB.

2.4. Signal analysis

In the literature, the wear progression of stamping tool is successfully studied using force, audio and AE data [6, 15-18]. The signal from these sensors have been monitored using different techniques in the literature. For example, Principal Component Analysis (PCA) to analyse force data, Relative Cumulative Spectral Power Index (RCSPI) to analyse audio data, and AE RMS, AE peak and AE mean-frequency to analyse AE data. As these techniques and signal features have been successfully demonstrated to study wear progression, therefore only these techniques are used in this study to compare the performance of force, audio and AE data.

The b-values (co-efficients) from the PCA analysis of the force data is used to characterise the force signatures. By calculating the b-values from the PCA analysis, an attempt will be made to track the change in force signature due to tool wear. The audio RCSPI feature is the cumulative frequency domain magnitudes of the audio signal corresponding to each part, divided by the first part. In this study, the

audio RCSPI feature was studied over a frequency domain of 0-1 kHz, 3-4 kHz and 5-6 kHz. To analyse the AE data, AE RMS, AE peak and AE mean-frequency is analysed for each part to understand the change in AE signal behaviour due to wear progression on the stamping tool.

3. Result and discussion

3.1. Wear examination on the wall of the stamped parts

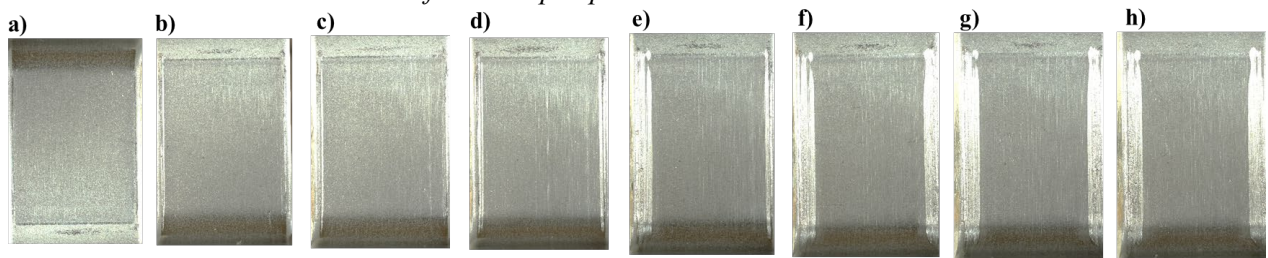


Figure 3: Wall of stamped parts of Part a) 1 b) 50 c) 100 d) 150 e) 200 f) 250 e) 300 f) 350 g) 400 h) 450 (Audio and force test)

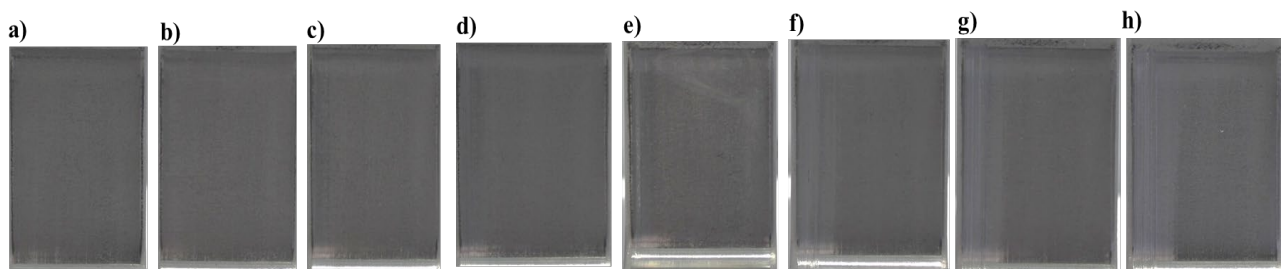


Figure 4: Wall of stamped parts of Part a) 1 b) 50 c) 150 d) 185 e) 220 f) 270 e) 280 f) 305 g) 375 h) 415 (AE test)

The side wall of the stamped parts was visually inspected to understand severity of the wear. As observed from Figure 3 and Figure 4, the wear initiates from the edges of wall of the stamped parts. For the stamping test performed using audio and force sensor, the wear is visually visible from 200 parts. The severity of wear increases and spreads towards centre with the increase in part number. From part 250, the wear is observed at both the edges of the stamped parts (Figure 3 f). For the stamping test performed using AE sensor, the wear initiates at the edges of stamped parts from part 220. Similar to Figure 3, as the part number increases, the severity of wear increases and spreads towards centre. However, unlike Figure 3, the wear is observed only at one edge in Figure 4. This is because of distinct and rapid growth behaviour of galling wear [20-21].

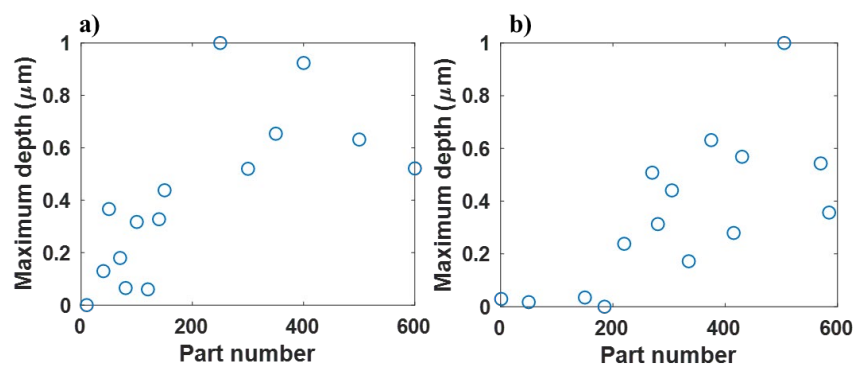


Figure 5: Maximum profile depth from the surface profile of a) Force and audio test b) AE test

To quantitatively measure the wear on the stamped parts, the maximum profile depth wear feature was used. In Figure 5, this maximum profile depth was normalised, based on the smallest and largest depths measured in each case. From Figure 5 a), we can observe that, the variation of maximum profile depth is mainly observed after 200 stamped parts. Similarly, from Figure 5 b), the variation of maximum profile depth is also observed after 200 stamped parts. These results in Figure 5 are in agreement with the visual observation of stamped parts in Figure 3 and Figure 4. However, it is worth noting that there is a difference in the threshold values of maximum profile depth at which the wear on the surface becomes severe, due to different profile width measurement adopted in the study. It can be seen that this threshold value is ~ 0.6 in Figure 5 a) and ~ 0.2 in Figure 5 b). The repeatability of maximum profile depth wear feature to indicate unworn and worn parts shows that it can be used for quantitative wear measurements.

3.2. Signal analysis of force, audio and AE data

Figure 6 represents the b1 and b3 coefficient values from the PCA analysis of punch force signatures. An increase in b-values indicates an increase in a variation mode of the punch force over the course of the production, and a constant b-value indicates near steady state conditions over the course of production. In this study, Figure 6 a) shows an increasing trend of b1 values, which indicates an increase in the most significant punch force variation mode. Figure 6 b), a neutral trend of b3 values indicates there is no change in the signal for the third most significant punch force variation mode. In this study, only the b1 value captured the wear of the tool.

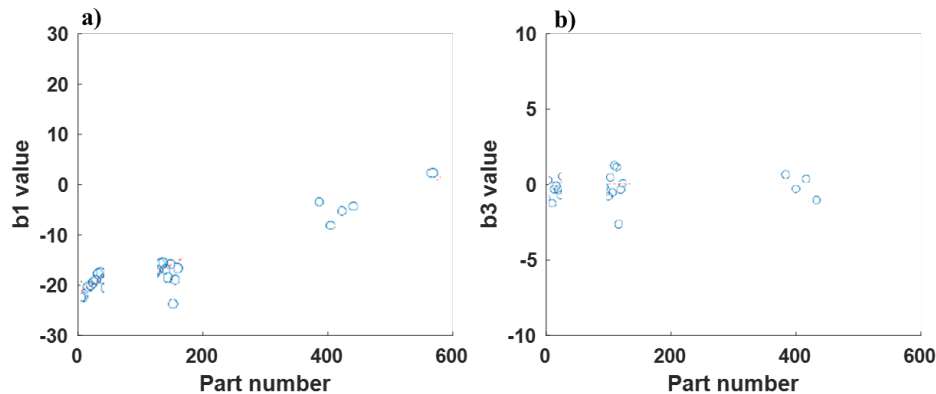


Figure 6: Best value from PCA of force data a) b1 value b) b3 value

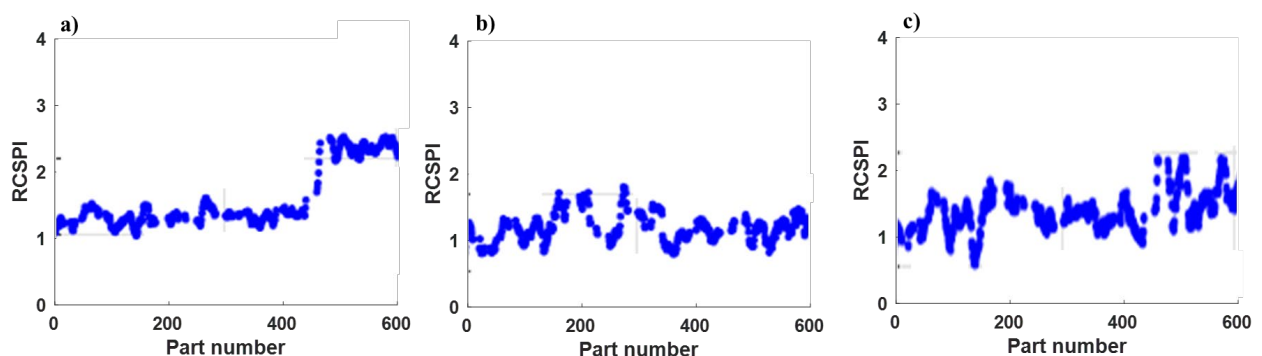


Figure 7: Relative cumulative spectral power index (RCSPI) in audio frequency range of a) 0-1 kHz b) 3-4 kHz c) 5-6 kHz

Figure 7 represents the RCSPI signal for each stamped part. The RCSPI is calculated over a 1 kHz wide distinct audio frequency bands. From Figure 7 a), the RCSPI value is nearly constant until part 500 and later a sudden increase in RCSPI value is observed. After part 500, a steady state of RCSPI values

was observed and did not show any further evidence of an increase in RCSPI values with increase in severity of wear. In Figure 7 b), the RCSPI values is nearly constant and no evidence of wear progression is observed. In Figure 7 c), the RCSPI values is nearly consistent until part 500 and later a minor trend in variation of RCSPI values is observed. From this audio analysis, we can observe that the galling wear information is mainly in the audio frequency range of 0-1 kHz.

Figure 8 represents the AE time and frequency domain features. In Figure 8 a)-b), the AE RMS and AE peak behaviour is nearly consistent until part 220. This consistency in time domain features is due to the unworn condition of the tool. The variation in AE RMS and AE peak behaviour is mainly observed after stamping 220 parts, which is attributed to the worn conditions of the tool. The repeatability of AE RMS and AE peak to indicate unworn and worn condition of the stamping tool shows that it can be used for the fault diagnosis. In Figure 8 c), the variation in trend observed from part 220 is in agreement with the variation indicated by the time domain features (Figure 8 a)-b)). However, the downward slope indicated by the AE mean-frequency from part 100 to part 220, was not indicated by the AE time domain features. This downward slope is mainly due to the presence of high energy AE events with low amplitude in between the continuous AE signal. From Figure 8 c), the AE mean-frequency for part 1-100 are unworn parts, part 101-220 are due to galling initiation and part 220-600 are due to worn condition of the stamping tool.

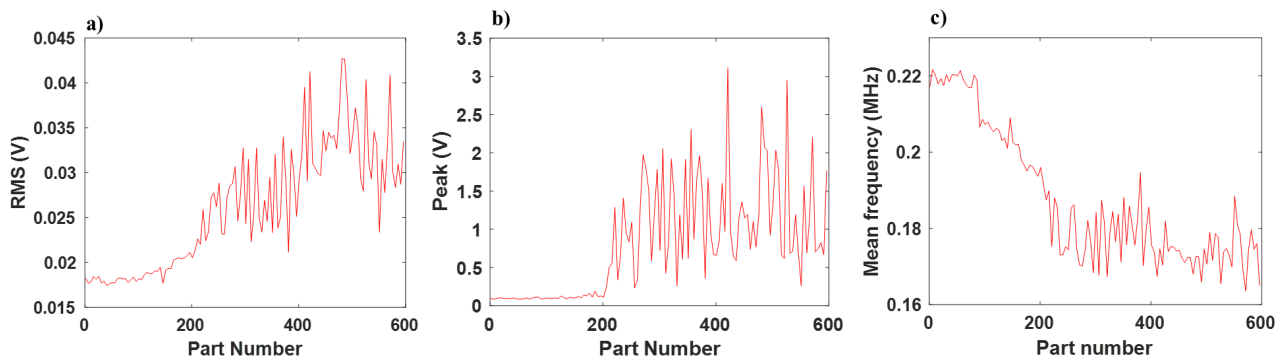


Figure 8: a) AE RMS b) AE Peak c) AE mean-frequency

3.3. Comparison of force, audio and AE data with profilometry wear measurements

When we compare the profilometry wear measurements (Figure 5) with the force, audio and AE features (Figure 6, Figure 7, Figure 8), we can observe that the force data and AE data are in agreement with the maximum depth wear measurement features. From the PCA analysis, the value of b1 increases after part 200. Similarly, the value of maximum depth wear measurement feature increases after part 200. Therefore, the b1 value from the PCA analysis of punch force is in agreement with the maximum depth wear measurement feature. In the audio analysis, the variation in RCSPI feature for the frequency bandwidth 0-1 kHz, is mainly observed after 500 parts are stamped. Comparing this RCSPI trend with the maximum depth wear measurement feature, the indication of wear initiation by audio feature is much later than the wear indicated by the profilometry wear measurement. In the AE time domain analysis, the AE RMS and AE peak profiles are in agreement with the wear indicated by the maximum depth wear measurement feature (after 220 parts). This wear on the stamped parts was also visible to the naked eye (Figure 4). However, the wear indicated by the AE mean-frequency occurs prior to the wear indicated by the maximum depth wear measurement feature and visual observation of the stamped parts (Figure 4). Therefore, from these observations, PCA analysis and AE time domain features can be used to study unworn and worn condition of the stamping tool and AE mean-frequency feature can be used to predict the onset of wear initiation – i.e. much prior to the observation of wear.

4. Summary

This study analysed the wear on the stamped parts using force, audio and acoustic emission. The force, audio and AE features were compared to predict wear progression on the side wall of the stamped parts. In the qualitative correlation of audio, force and AE features with the wear measurement feature, it was observed that AE and force features were in strong correlation with the onset of wear on the stamped parts. Compared to audio and force, AE mean-frequency feature was observed to predict the onset of wear prior to the visual observation of wear. This study lays a strong foundation for further investigation of a common signal processing technique that can be adopted for smart sensor monitoring approach of sheet metal forming processes.

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