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The acoustic emission (AE) controlling method of the electric sheet blanking process – a comparative study of selected data mining methods

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Abstract

The article presents an experimental stand to assess the state of punch in the process of sheet blanking. Blanking trials were carried out on an eccentric press. During all the trials, there were recorded signals of acoustic emission (AE) that accompanied the process of blanking. For the recorded AE signals, the methodology of data preparation and analysis was presented. On that basis, the results of the assessment of the state of the punch were presented, and they employed five methods of visualization: Andrews curves, Principal Components Analysis, Linear Discriminant Analysis, a modified method of Stochastic Neighbor Embedding and Sammon Mapping. The aim of the work was to assess the possibility of using visualization methods to predict the condition of the tool on the basis of acoustic emission signals in processes carried out in extremely short times.

Keywords: acoustic emission, data acquisition, data preparation methods, visualization methods, process duration, process speed, punching, manufacturing, Andrews curves, PCA, LDA, tSNE, Sammon Mapping

1. Introduction

Research employing acoustic emission is very common, and one of the most important is nondestructive testing (Miller et al., 2005), but the AEA application results, where the acoustic wave emitted by an object or system is recorded are also used in various areas of manufacturing, such as:

- the food industry, e.g. testing the quality of food products (Jakubczyk et al., 2017; Marzec et al., 2005; Ranachowski, 2010);
- the automotive industry, e.g. engine diagnostics (Bejger, 2008; Brambilla et al., 2021; Raunmiagi, 2011);
- construction, e.g. assessment of the technical condition of buildings (Kossakowski, 2013; Li et al., 2021; Świt et al., 2013);
- the machine industry, e.g. monitoring of the tools or process condition (Barschdorff & Haupt, 2000; Fillatreau et al., 2008; Jemielniak et al., 2010; Moszczyński & Czyżewski, 2008; Skåre et al., 1998; Teti et al., 2010; Twardowski et al., 2021).

In the preliminary research (Błażejewska, 2012) the authors gathered works concerning the last of the areas mentioned, the monitoring of cutting tools, and published within a twenty year period from 1990 to 2011. The list comprises over 200 publications,

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of which 20% are studies about the applicability of acoustic emissions. Such a significant contribution of scientific papers about the employment of acoustic emissions is dictated by the many advantages of this method. One of the most important advantages is the possibility of monitoring the tool if it is located in difficult to reach places. In the case of the elements punched from electrical sheets, e.g., as presented in Figure 1, the shape of the tool is very complex. The developed curve prevents the visual monitoring of the state of the tool, as the frequent refitting is problematic and time-consuming. Early detection of tool wear (its blunting) allows maximum use, and, at the same time, there is no fear of the emergence of defects that might disqualify the product.

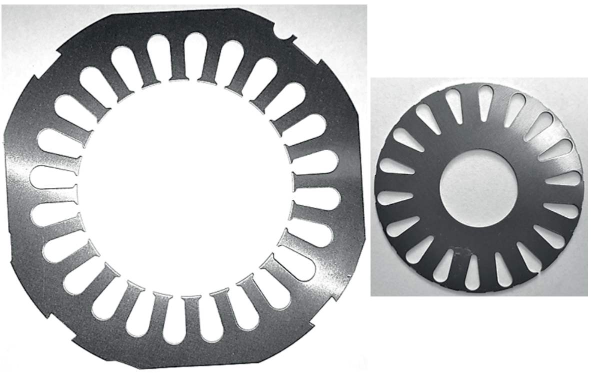


Fig. 1. Examples of elements punched from electrical sheets

Acoustic emission measurement with regard to the process of blanking differs significantly as compared with the technological processing of metal. In the research conducted for micromilling (Jemielniak et al., 2008), turning (Yamaguchi et al., 2007), and drilling (Patra, 2011), the time of signal recording ranges from 10^0 to 10^2 sec. In the case of metal forming processes, the duration of the analyzed signal is significantly shorter, and for forging (El-Galy & Behrens, 2010) it was up to the maximum of 10^{-1} sec.

Punching is a technological process consisting in cutting an element of any shape from a sheet. The shape of the element to be cut depends on the geometry of the tool, which consists of a die and a punch. In one operation, the punch moves down, and when it reaches the lower-end position, it moves up. Depending on the design of the tool and the thickness of the sheet, the punch travels from a few to several millimeters during one cycle. However, the cutting process itself, and thus the time of acoustic signal emission, is much shorter. This time depends only on the thickness of the sheet being punched out. The electrical sheets used for the elements of electric motors are less than 1 mm thick. Therefore, the punching time is very short and may take less than 10^{-2} sec., as shown in Figure 2.

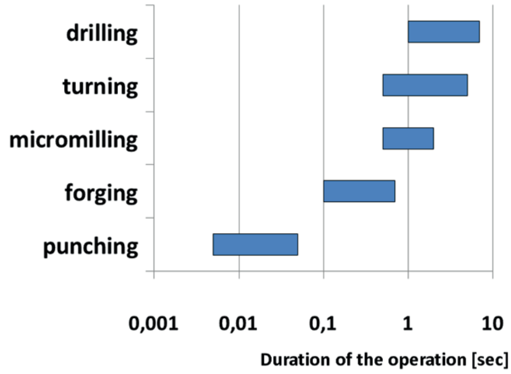


Fig. 2. Range of typical execution times of selected manufacturing processes

In the presented study, during the process of electrical sheet blanking of elements which were 0.35 mm thick, the duration of the recorded signal was shorter than $7 \cdot 10^{-3}$ sec. (Fig. 3).

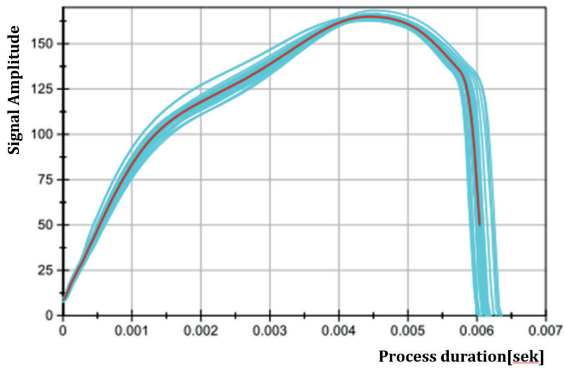


Fig. 3. Time of the punching process (recorded series of 30 signals)

2. Experimental laboratory stand

In the laboratory of the Institute of Manufacturing Techniques, a prototype technological line was built in accordance with the assumptions of the Industry 4.0 concept. The line included: electrotechnical tape warehouse, feeding system, and eccentric press. The technological line was equipped with sensors, and the signals coming from the sensors were collected in the SCADA system built on the basis of Kistler industrial computers. According to the paper (Moszczynski et al., 2008), the amplitude of the acoustic signal depends on the stage of the punching process (Fig. 4).

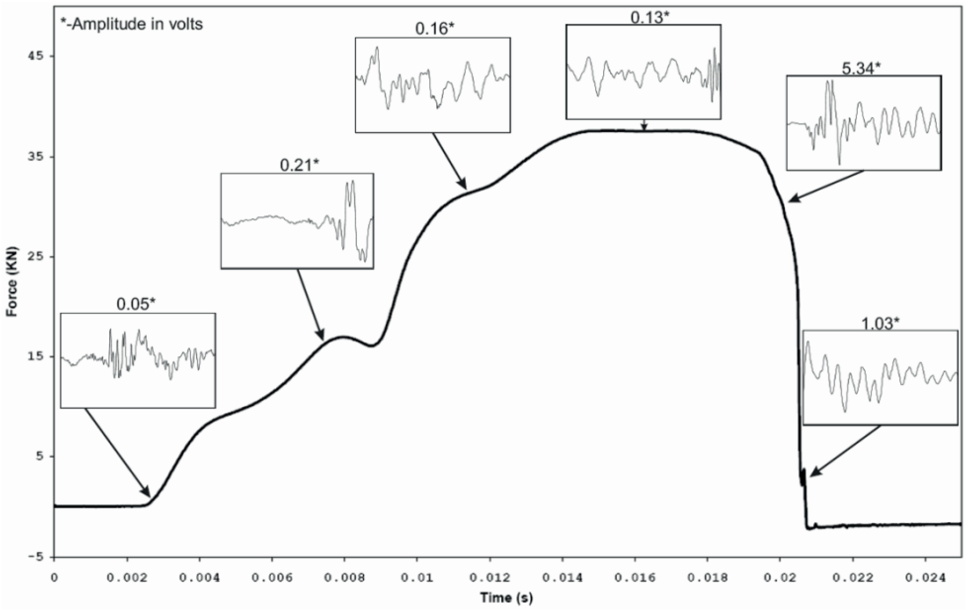


Fig. 4. Blanking force in the time function; loss of structural integrity (marked with a green arrow) causing a sharp increase in the amplitude of the acoustic emission signal (Moszczynski et al., 2008)

In the fifth stage of the process, shown by the green arrow in Figure 4, the cohesion of the material is lost. At this stage, there is a rapid decrease in the punching force, and at the same time, the value of acoustic emission measured by the amount of released energy is the highest. Figure 4 shows graphs for each stage of the process, where the numerical values shown in [V] correspond to the "peak-to-peak" amplitude value.

In the study, a blanking tool was used (Fig. 5), which was placed on the eccentric press PMS-16C. In the experiment, two punches were used: a sharp one (Fig. 6a) and one that was worn (but without any decrement failures, Fig. 6b).

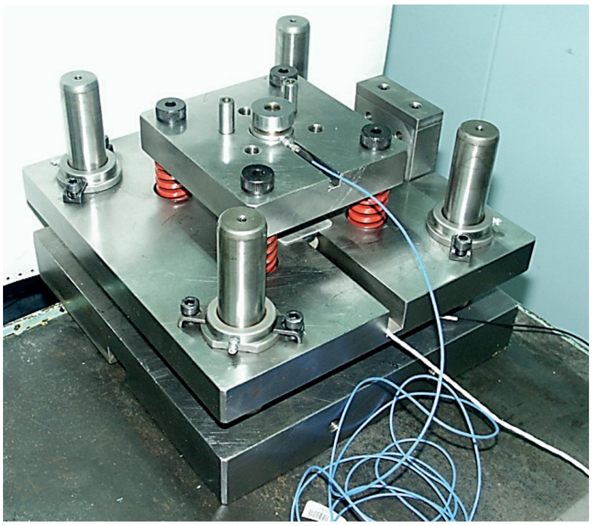
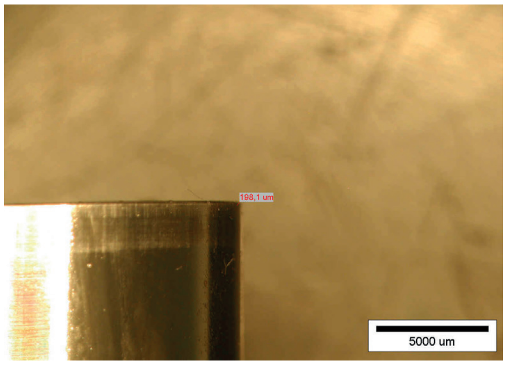


Fig. 5. Photo of the punching/blanking tool used in the control station – visible wires of force sensor (blue arrow) and acoustic emission sensor (green arrow)

a)



b)

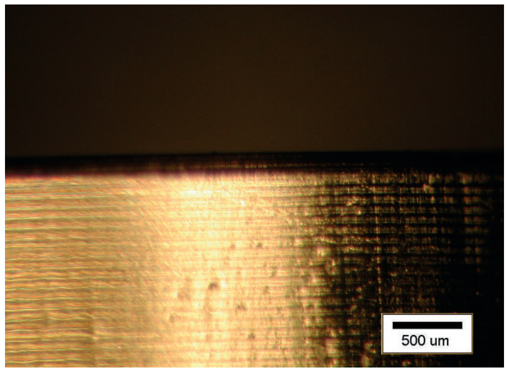


Fig. 6. Blunt punch: a) ×6,3 magnification (it shows the edge radius of the blunt punch – 0.2 [mm]); b) ×50 magnification

The experimental stand was equipped with a set of sensors for recording the process parameters of blanking. In addition to the AE signals, the process force was recorded as well as the punch displacement. Acoustic emission signals were recorded using the MISTRAS program by PAC. The measurement schema is presented in Figure 7.

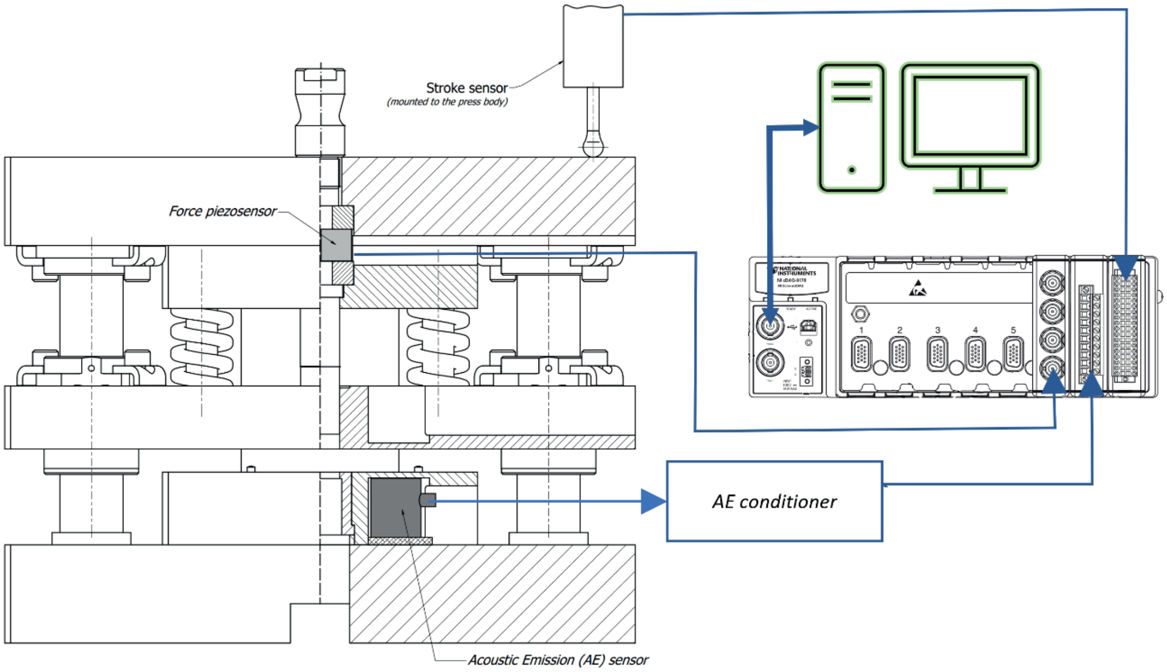


Fig. 7. The measurement schema of the experimental stand used during the investigation

According to the results included in the paper (Moszczyński & Czyżewski, 2008), during the detection stage, the level of acoustic emission remains at a fairly low level in all the initial stages of the process. Only at the moment of the damage failure in the blanked material does the signal level (gauged in volts) increase by one order of magnitude. Figure 4 presents the distribution of the levels of signal in the subsequent phases of blanking (max. value 5.34 V, marked in Figure 4 with a green frame)

3. Acquisition and data preparation

An acoustic emission signal is emitted during a single punching process. Figure 8 presents an example of a single observation of the acoustic emission event recorded during the punching process with the sharp punch. The recording of a single emission starts just before the punch comes into contact with the punched material and ends when the punch ejects in the punched sheet. The total recorded emission time is less than 0.01 sec.

For the data acquisition of the AE signal recording the readymade MITRAS software was used. The program records a single observation as a series of consecutive fragments. The length of a single fragment is determined in the program. Each observation (shown in Figure 8) is described by 17 values, and these are mainly: run time number, onset of the impulse, rise time/accretion, sum up, energy impulse, amplitude, and so on. A detailed description can be found in part (Physical Acoustic, 2002). The table presented in Figure 9 shows examples of recorded measurements. Columns 1, 2 and 5 contain information records (no. of observation, tool condition, channel). Columns 3 and 4 contain the number of the next event recorded during a single punching and the time of its start. The following columns contain the characteristic values of the recorded AE signal (e.g. AE energy, amplitute, average frequency).

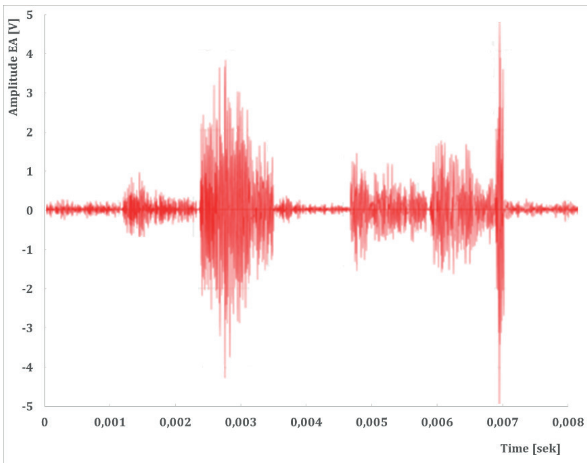


Fig. 8. Record registration of acoustic emission waveform while blanking with a sharp punch

No. of observation	Tool condition	HIT	REL. TIME OF TEST	CHANNEL	RISE TIME	COUNT	AE ENERGY	DURATION	AMPLITUDE	AVG. FREQ.	CNT TO PEEK	TRUE ENER	RISE FREQ	C MASS X	C MASS Y	AMPLITUDE/ RISE TIME
1	SHARP	1	0,00003363	1	9,25	56	9,86	254,5	61,22	220,04	2	25,49	216,22	90,06	0	6,618
		2	0,00003383	1	102,25	87	16,11	251,75	62,68	345,58	34	61,24	332,52	115,4	0	0,613
		3	0,00003385	1	253,75	89	11,55	255,25	62,98	348,68	88	36,54	346,8	95,42	0	0,2482
		4	0,00003387	1	7,5	104	38,89	255,75	73,72	406,65	3	398,92	400	91,71	0,02	9,829
		5	0,00003389	1	10,25	79	8,19	250,25	58,41	315,68	4	16,39	390,24	87,25	0	5,699
		6	0,00003434	1	171,25	112	1198,06	255,5	96,96	438,36	76	314570,63	443,8	132,29	12,05	0,5662
		7	0,00003436	1	32,25	107	1023,46	255,75	96,7	418,38	13	241977	403,1	121,13	9,25	2,999
		8	0,00003438	1	67,5	99	42,45	255,75	72,88	387,1	24	427,8	355,56	112,71	0,02	1,08
		9	0,00003441	1	209	96	513,75	248	96,48	387,1	82	104213,99	392,34	200,46	4,24	0,4616
		10	0,00003443	1	33	98	61,19	255,75	78,12	383,19	12	1008,42	363,64	84,81	0,04	2,367
		11	0,00003444	1	10,25	70	7,41	255,25	58,94	274,24	3	14,27	292,68	94,52	0	5,75
		12	0,00003620	1	214,75	70	38,04	255,75	71,59	273,7	57	352,04	265,42	147,38	0,01	0,3334
2	SHARP	1	0,00011855	1	12	65	10,41	250,25	66,02	259,74	3	36,41	250	56,97	0	5,501
		2	0,00011858	1	28,75	100	26,66	255,75	69,58	391,01	12	168,39	417,39	119,78	0,01	2,42
		3	0,00011860	1	4,5	33	4,45	231	60,37	142,86	2	6,92	444,44	43,52	0	13,42
		4	0,00011906	1	244,25	110	134,55	255	90,36	431,37	105	6858,95	429,89	184,75	0,26	0,3699
		5	0,00011909	1	11,5	76	7,53	255,75	59,12	297,17	4	14,75	347,83	91,76	0	5,141
		6	0,00011912	1	10	75	7	255,75	58,79	293,26	4	12,55	400	89,53	0	5,879
		7	0,00011913	1	30	94	98,9	255,5	79,39	367,91	10	2357,98	333,33	107,09	0,09	2,646
		8	0,00012051	1	9,5	52	5,01	252,25	59,88	206,14	4	7,59	421,05	74,72	0	6,303
		9	0,00012052	1	7,75	51	5,1	253,25	59,71	201,38	4	7,88	516,13	72,95	0	7,705
		10	0,00012054	1	96,25	110	50,3	255,75	74,82	430,11	45	630,27	467,53	112,31	0,02	0,7773
		11	0,00012056	1	10	68	6,8	254	59,71	267,72	4	11,97	400	109,83	0	5,971
		12	0,00012091	1	50,25	86	146,78	254,5	85,68	337,92	17	6370,45	338,31	108,64	0,25	1,705
		13	0,00012211	1	1	5	0,38	5,5	66	909,09	1	0,05	1000	1,2	0	66
3	SHARP	1	0,00010100	1	231,25	95	35,46	253,75	73,14	374,38	86	341,48	371,89	184,22	0,01	0,3163
		2	0,00010149	1	177,75	110	1164,21	252,25	96,87	436,08	81	301458,41	455,7	137,44	11,84	0,545
		3	0,00010152	1	120,5	106	60,66	255,75	75,33	414,47	47	931	390,04	103,2	0,04	0,6252
		4	0,00010155	1	216,25	102	626,16	255,75	96,93	398,83	85	138853,59	393,06	188,58	5,31	0,4483
		5	0,00010156	1	2,5	93	117,83	255,75	81,52	363,64	1	3315,24	400	111,69	0,13	32,61
		6	0,00010159	1	10,25	79	10,56	251,75	62,01	313,8	3	28,54	292,68	82,19	0	6,05
		7	0,00010333	1	252,5	63	74,42	255,75	83,74	246,33	62	2011,3	245,54	202,62	0,08	0,3316

Fig. 9. The table presents the recording of the acoustic emission signal for three series of punching

A single observation marked in the table shown in Figure 9 consists of 13 parts, each of which is described in 12 variables. In the research, two series of blanking were performed for two states of the tool. In each series, 30 elements were blanked.

The resulting data for modeling have been prepared in accordance with the methodology presented in the paper by (Grzegorzewski & Kochanski, 2019). Two tasks were highlighted: data cleaning and data transformation. In the first part, there were aggregated values describing the impulses of acoustic emission recorded in one observation. The average duration of a single observation of the sharp punch was 0.00244 sec., and for the blunt one 0.00247 sec., with the corresponding standard deviation of 0.00030 and 0.00036.

As part of the data transformation task (in accordance with the adopted methodology), aggregation or averaging activities were performed. Quantities that were characterized by low variability were replaced with an average value, e.g. amplitude. Other figures have been aggregated (AE energy, true energy, time). A new parameter is, for example, the total energy released in a single observation aggregated as a function of time. The descriptor Total AE energy is the sum of the acoustic emission energy released in all impulses recorded during a single process of blanking. All transformed data replaced with aggregated or averaged values are shown in the table in Figure 10. The fragment of the table shown in Figure 10 shows the new attribute names, taking into account the data transformation task, e.g. replaced by means of amplitude. After such a transformation of data, each observation is saved as a single vector described by six variables: total AE energy, means of amplitude, means of average frequency, total true energy, means of rise frequency and total time.

The transformed data, after the linear normalization of the min-max type, allowed the task of cleaning the data to be completed, which mainly included the outlier of the detecteddata. For this purpose, the visualiz ation method utilizing Andrews curves was used (Andrews, 1972), described by the Equation:

$$f_x(t) = x_1/\sqrt{2} + x_2 \sin(t) + x_3 \cos(t) + x_4 \sin(2t) + x_5 \cos(2t) + \dots \tag{1}$$

where: $t \in <-\pi; \pi>$ and x_i–i – no. of attribute.

Andrews curves delineated for the sharp and blunt punches are shown in Figure 11.

Tool Condition	No. of Observation	TOTAL AE ENERGY	MEANS OF AMPLITUDE	MEANS OF AVE. FREQ.	TOTAL TRUE ENERGY	MEANS OF RISE FREQ.	TOTAL TIME
SHARP	1	2968,960	74,223	349,892	663102,730	350,193	2,56944E-06
SHARP	2	503,870	68,418	348,898	16484,160	443,531	3,55324E-06
SHARP	3	2089,300	81,363	363,933	446939,560	364,130	2,33796E-06
SHARP	4	2583,890	80,045	383,431	538287,250	370,513	2,36111E-06
BLUNT	1	858,170	73,270	378,753	134219,190	390,714	2,34954E-06
BLUNT	2	1032,360	68,649	322,545	135423,970	382,474	2,36111E-06
BLUNT	3	1332,240	73,769	331,817	148904,780	432,755	2,33796E-06
BLUNT	4	872,170	73,671	356,288	74016,300	380,310	2,33796E-06
BLUNT	5	709,480	71,606	366,676	96173,580	411,850	2,34954E-06
BLUNT	6	652,950	72,973	343,049	52850,850	366,678	2,34954E-06
BLUNT	7	725,610	71,609	374,119	46752,810	395,120	2,34954E-06

Fig. 10. Table of transformed data

a)

b)

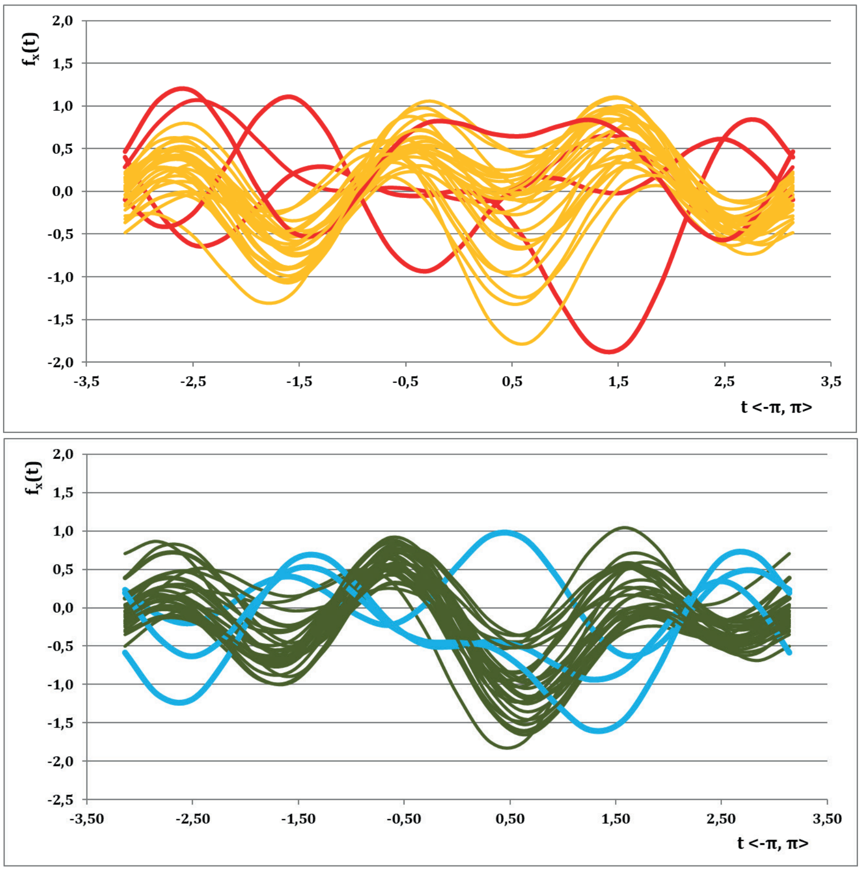


Fig. 11. Andrews curves for two of the analyzed series of observations for the punches (different color lines indicated the generated run time of the outlier): a) sharp; b) blunt

According to the definition presented in the work by Hawkins (1980, p. 1) the data outlier is considered to be "an observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism". The method based on Andrews curves (Equation (1)) was used as a visualization method. Visualization methods make it possible to intuitively detect observations that behave differently from others. From the above statement, it follows that every observation for which the delineated curve is of a different character was considered to be the outlier. In the graphs in Figure 11a and b lines that have different shapes than the others have been marked with different colors. According to the cited definition, they can be treated as outliers.

4. Data modeling

The effectiveness of data mining depends on involving a person directly in the analysis process and a skilful combination of flexibility, creativity and general knowledge of a human with the incredible computing capabilities of modern computers. Data visualization allows the integration of human perceptions with huge data sets processed by computers. The basic assumption of visualization is to present data in a form that allows for easy insight into the data, drawing conclusions and direct influence on the data.

In order to determine the possibilities of monitoring the state of the tools, five different algorithms were used in the modeling. The first algorithm was the one applied earlier, namely the multidimensional visualization algorithm – Andrews curves and the commonly known algorithms such as: PCA (Principal Component Analysis), LDA (Linear Discriminant Analysis), SM (Sammon Mapping) and tSNE (Stochastic Neighbor Embedding). All employed algorithms (Andrews, PCA, LDA, SM and tSNE) used data after data cleaning and data transformation tasks (as described in Chapter 3: *Acquisition and data preparation*).

In the Andrew curves method, as shown in Figure 11, each multidimensional observation is transformed into a sinusoidal-shaped curve. The remaining four methods (PCA, LDA, SM, tSNE) reduce the multidimensional space of the signal vector emission to the two-dimensional space presented in graphical form – the scatter plot chart.

The comparison of the Andrews curves can be obtained in two ways: by specifying the distance between the two curves in the entire field of function, or by determining and comparing the value of the Andrews' function at selected points. In order to distinguish between the curves corresponding with the two states of punch the second method was chosen, and it was based on the characteristic points of the obtained curves. Six points were designated, and they corresponded with the values of the Andrews function for $t = -\pi$; 0; $1/10\ \pi$; $1/5\ \pi$; $3/10\ \pi$; π. For each observation, that is, for its corresponding curve, the calculated points of characteristic values were summed. The total sum ranged from 4.6 to 14.2. As shown in Figure 12, in most cases, the calculated values, ranged from 4 to 8 for a sharp punch, and for blunt punches from 10 to 14. Both types of punches occurred with almost equal frequency within the range of 8 to 10. It was observed that among the cases that were different, as presented by numbers 2 and 39, they were qualified (shown in Figure 11) as data outliers.

In the second part of the study, algorithms were used to visualize multidimensional observations by reducing dimensionality.

In four selected methods, i.e. PCA, LDA, SM, tSNE, the six-dimensional observation record was reduced to two dimensions, which makes the visualization of each observation record possible as a point in the two-dimensional space $\mathbb{R}^2(x_1, x_2)$, where x_1 and x_2 coordinates represent the location of the observation in transformed space.

Figures 13–16 show examples of modeling results using space-dimensionality reduction algorithms. On all graphs, fixed arbitrarily, there were hypothetical boundaries separating the areas of concentration which were corresponding with the two states of punch and the space of unspecified status between them. The boundaries imposed by the authors are presented with green lines. It can be observed that there appear points belonging to the opposite type in the concentration, e.g., among the identified blanks with a sharp punch, there are cases corresponding with the process of blanking/punching with the blunt punch. The question of these points still remains to be answered. Figure 13 presents the result obtained as an outcome of the reduction of the dimensionality by the use of the PCA.

The effect of reducing the dimensionality by the use of the LDA algorithm is demonstrated in Figure 14.

In the area recognized as observations which were recorded during the process of punching with a blunt punch, there were two values derived from measurements carried out while cutting with a sharp punch. One of them is the same as the one which was considered the outlier in the method of Andrews (Fig. 11a and Fig. 12), and it was indicated in the graph point in the PCA method (Fig. 13).

In the algorithm tSNE the dimensionality reduction process (the transformation in two-dimensional space), in each case, is started with a randomly chosen vector. As a result of the multiple re-converting, the results did not differ significantly. The drawings in Figure 15 demonstrate an example of the result.

Also here, among the three points placed in the area recognized as the observations recorded while cutting with a sharp punch, one of them is the outlier which was discussed in all the previous types of modeling.

The last of the tool quality assessment methods selected for visualization is Sammon Mapping (SM). The results are shown in Figure 16.

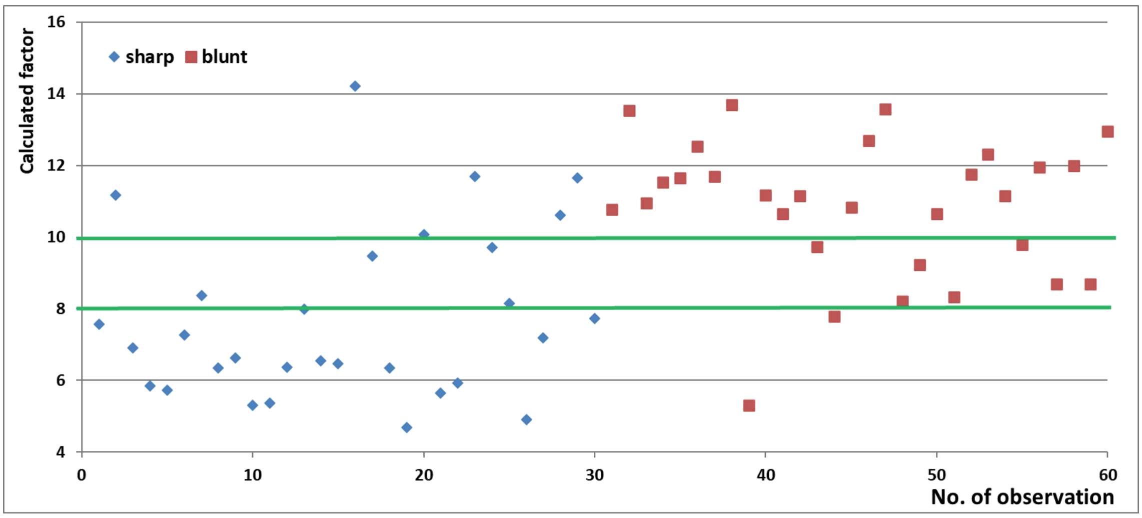


Fig. 12. Volumes calculated from five points located on Andrews curves for each observation; the horizontal axis of the graph corresponds to the consecutive number of observations

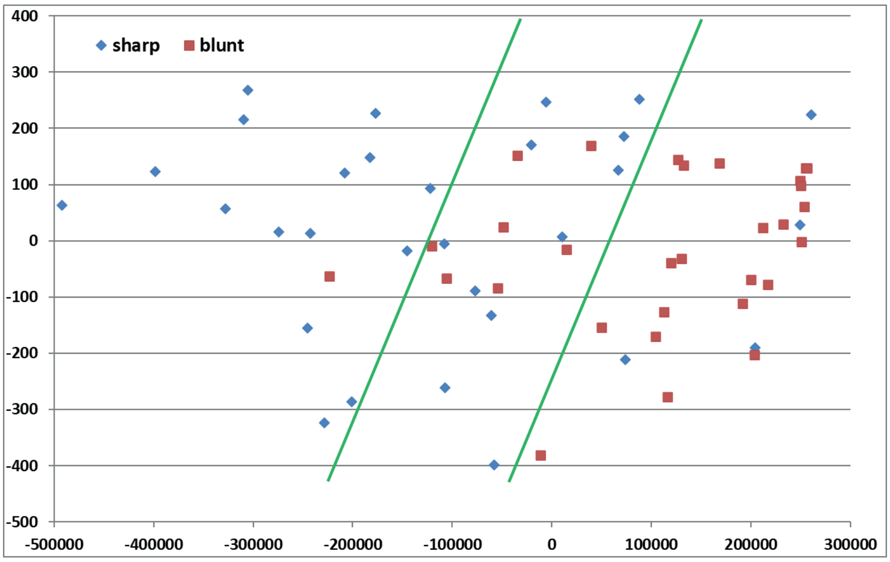


Fig. 13. Data visualization by the use of the PCA method

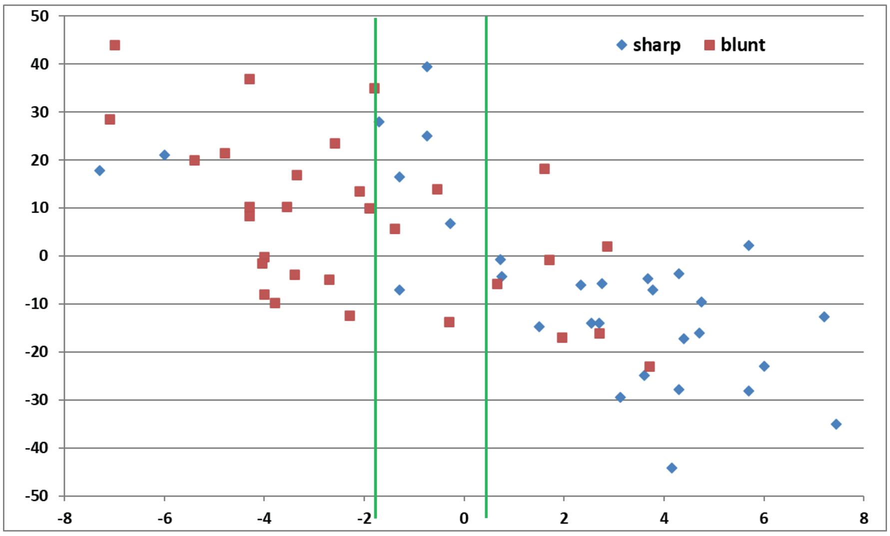


Fig. 14. Data visualization by the use of the LDA method

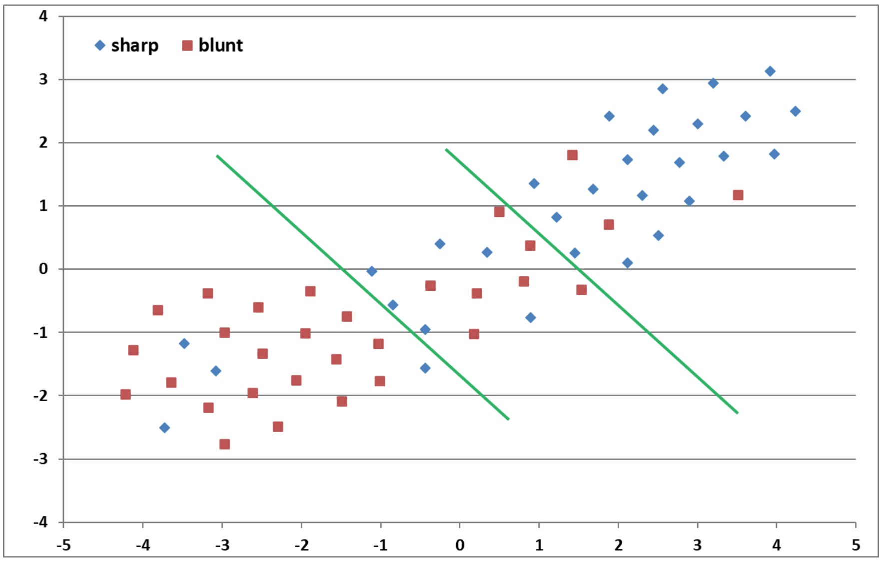


Fig. 15. Data visualization by the use of the tSNE method

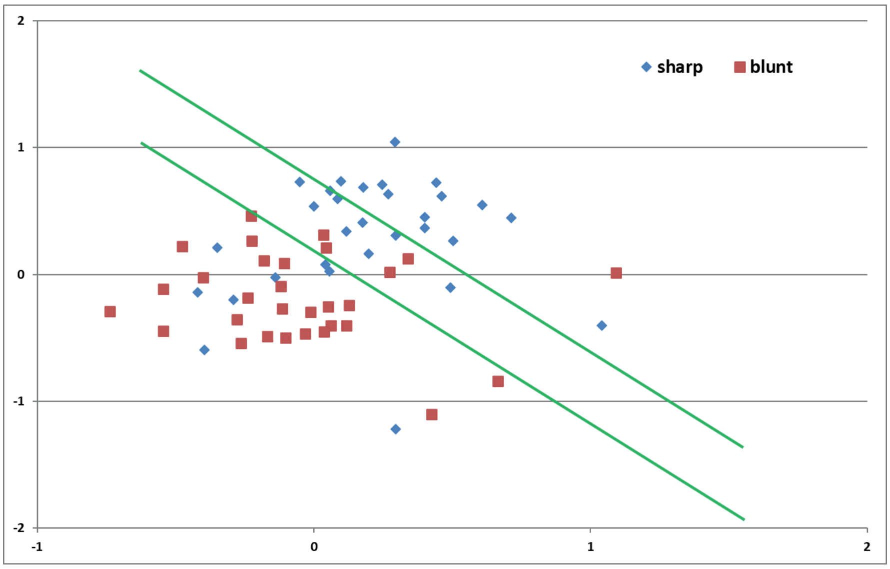


Fig. 16. Visualization of the Sammon Mapping method

5. Summary

Table 1 presents the summary of the obtained results. Due to the nature of the algorithm tSNE (the element of randomness in the calculations), the demonstrated results are the average results derived from several trials. As an example, the LDA method identified 22 results of measurement (for 30 conducted observations) as performed with a sharp punch, and 20 performed with a blunt one (also in 30 trials conducted). Similar values were obtained in other types of modeling. The weakest ability to forecast was demonstrated by the PCA method. Out of thirty punches performed with a sharp punch, only 15 cases were correctly indicated.

Table 2 presents a number of correct predictions calculated as a percentage of the total number of observations made.

The best results were achieved by using Sammon Mapping. The LDA method indicated the highest number of false forecasts (7 + 2).

The character of errors is also worth noticing. In the four methods described above, the sharp punch was more frequently indicated as blunt than the other way around. The number of indications of the sharp punch as the blunt one in four methods: Andrews, Sammon Mapping, PCA, tSNE, was 6, 6, 4 and 4, respectively. The blunt punch was only classified as sharp more frequently in the LDA method, as many as 7 times, and the sharp one was classified as blunt two times. From the perspective of the conducted process, it is a safer condition to qualify the sharp punch as blunt.

In all the considered methods there were cases of non-matching. The lack of unambiguity was noted in the largest number in the PCA method and in the smallest number in the Sammon Mapping. In the first case, it was 18 events, and in the second, 6.

Table 1. Summary table of the results

Tool conditions	Measured									
	Andrews		PCA		tSNE		Sammon		LDA	
Predicted	sharp	blunt	sharp	blunt	sharp	blunt	sharp	blunt	sharp	blunt
Sharp	20	2	15	1	20	3	22	1	22	7
Blunt	6	21	4	22	4	20	6	24	2	20
Undeterminated	4	7	11	7	6	7	2	4	6	3

Table 2. Percentage summary of correct predictions [%]

Tool conditions	Andrews		PCA		tSNE		Sammon		LDA	
	sharp	blunt	sharp	blunt	sharp	blunt	sharp	blunt	sharp	blunt
Percentage of correct predictions	66.67	70.00	50.00	73.33	66.67	66.67	73.33	80.00	73.33	66.67

6. Conclusion

In conclusion, it should be stated that the results of the preliminary studies demonstrated the possibility of using only the acoustic emission signals, without any additional sensors, to assess the state of the tool in the process of blanking. This is all the more important since, in the processing in which the duration of the operation is so short ($5 \cdot 10^{-3}$ sec.), it is practically impossible to correlate the signals coming from various sensors and recorders. The duration of the process is comparable to the delays occurring between different measurements of recorded lines and can be caused by various factors. What significantly affects the acoustic emission signal is the thickness of the sheet. Significant, although still within the acceptable norms, the double-digit differences in the thickness of the sheet are perceived as acoustic emission signals of a different character.

The second reason is the variable properties of the layer covering the electrical sheet. The significant influence of the coverage on the process of punching was highlighted in the paper [24]. The above means that when changing the sheet material, it may be necessary to calibrate the system. However, this requires confirmation in further research

The selected methods used, in accordance with the assumptions of visualization methods, showed the capability of these methods to indicate clusters without the use of complex calculation algorithms, making immediate interpretation of the result possible.

Further research should include both the data preparation process as well as replacing the existing method of the arbitrarily shared space within the algorithmic method. The data collection/set should be extended to include the results of acoustic emissions derived from punching sheets from different suppliers.

Moreover, at the next stage, visualization methods used in the research should be adopted to create a human – machine interface where the state of the tool will be presented dynamically during the production process.

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