Analysis of the guiding column and sleeve cooperation in the linear slide bearing of the punching die head-punch block

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Abstract. A proper cooperation of the guiding column and sleeve in the linear slide bearings of the punching die head-punch block is very important in the context of alignment between the punch and the die. Multiple factors like the shaft and sleeve tolerances, contact surface roughness or the type of loading applied to the bearing may have an effect on the movement of the mechanism. In the paper authors focus on the influence of the linear slide bearings distribution on the punching die plate on the stress distribution on the column and the sleeve as well as on the deflection of the head-punch block. It is especially important for the punching dies with one-sided guiding that enables moving it toward the center of the material to perform a designed perforation pattern. Considering the machines for polymer composite belt perforation, the deflection of the head-punch block has to reach its minimum since very small punch-die clearances (below 1 % of the hole diameter) are used. The presented FEM analyses provide a lot of useful information and enable designing effective constructions of the punching die. Additionally, the effect of the return spring system was also modelled.

1. Introduction

Due to the variety of the mechanical properties of the polymer composite belts, the influence of the processed material features on the construction of the machines used in the process is clearly visible. This effect can be observed for polymer belts [1–9] as well as for different types of materials, like natural polymers [10–12] and unclassical materials [13–17]. However, the constructional features of the designed machines also have a lot of influence on its performance characteristics like strength, stiffness, kinematics and dynamics. In the presented research authors focused on the influence of the guiding column distribution in the punching die on the punch deflection, stress distribution and cooperation between the column and the sleeve.

Linear guides are widely used in the machine design and the analysis of their performance can provide a lot of useful data [18–20]. For example, it was proved that shape deviations of the column or the sleeve like ovality or multiangularity have an impact on the alignment of these components and may result in generating increased contact pressure in the components [21, 22]. It is especially important for punching dies for belt perforation, where the punch-die clearance has to be very small – approx. 0.5–1 % of the punch diameter. For that reason the machining process for these components has to be precisely done and proper information should be contained in the technical documentation [21, 22]. Beside the manufacturing process, the distribution of the guiding columns will also affect the properties of the machine, like head-punch stiffness, overall dimensions and the mass of the device, as well as the contact pressure distribution, which has an influence on the motion of the plate, generated...
frictional drag and life of the guiding system. For that reason authors decided to perform the analysis of the guiding column distribution for the above mentioned parameters and specify the constructional briefs which can be used in the design process of such constructions.

To obtain a wide spectrum of correlations, the analyses were performed for six types of guiding columns distribution which vary in the number of columns, the direction of the positioning and the pattern. For two guiding columns, horizontal (2H) and vertical (2V) distributions were chosen. For three guiding columns, the triangular pattern was chosen in the normal variant (3N) and the inverted one (3IN). For four guiding columns, rectangular (4R) and staggered patterns (4S) were analysed. All of the above-mentioned types of distribution are presented in figure 1. In order to maintain the possibility of comparison between different types of guidance, the distance between the punch axis and the axis of the first row of guiding columns c is constant and equals 285 mm. This value is restricted by the width of the perforated belt and allows the punching die to make a hole 250 mm from the belt edge. Additionally, the distance between the guiding columns in both directions a and b for a 3N type was analysed in order to test the influence of the compactness of the construction.

![Figure 1. Different types of the guiding column distribution in the punching die construction.](image)

2. Methodology of the research

The analysis was performed on the basis of the computer simulation results, which were obtained using Finite Element Method (FEM) in ABAQUS software [23]. The construction of the FEM model for each of the analysed cases is similar and one of the examples is presented in figure 2. The model complexity was limited to a few instances: the main one – head-punch block and proper number of guides where each consists of the guiding column and the sleeve. The sleeve is made of brass with Young’s modulus $E = 120 \text{ GPa}$ and Poisson’s ratio $\nu = 0.35$. The head-punch block and guiding columns are made of steel with Young’s modulus $E = 210 \text{ GPa}$ and Poisson’s ratio $\nu = 0.33$. All the instances were meshed with tetrahedral C3D10 elements and it was densified on the contact surfaces between the head-punch block, columns and sleeves to 25 elements on the circumference of the axially symmetrical connection parts.

To map the real conditions which occur during the belt perforation process, proper loading, boundary conditions, contacts and constraints have to be specified in the FEM model. The loading was divided into four different total forces specified as pressure applied to the partitions separated from the top or bottom surface of the head-punch block. Perforation force $F_p$ is responsible for the generation of the necessary stress on the sheared cross section of the belt to break the material and separate the scrap from the belt. Since this force is transferred from the piercing punch by the chunk to the circular plate and then by the threaded joint to the head-punch plate, the pressure was applied to the surface of the washers of the bolt-nut connection. Its value was determined based on the experimental research [4] as a maximum value for the stiffest belt with the highest strength TFL15S with 20 % surplus and
equals 3372 N. The next two forces come from two different sets of spring: force from the return springs $F_{RS}$ which equals 260 N and force from the blank holder springs $F_{BH} = 143$ N were applied to the surface inside the socket, in which the above mentioned springs are embedded. Of course, the springs have an effect on the plate deflection, but because the stress and the deformation of the springs is not the subject of this research they were neglected as a result. Their influence was modelled with the weightless springs which connect proper reference points (coupled with the spring socket inner surface) to the ground and have specified spring constants. Last load $F_{PP}$ is the sum of all previously mentioned forces and represents the force generated by the pneumatic drive and transferred to the pressure plate. Because the bottom plate was removed from the model, the boundary condition which takes away all degrees of freedom was applied to the cylindrical surfaces on the bottom of the columns. In this model, it was assumed that sleeves are rigidly mounted in the head-punch plate and the contact between the inner surface of the sleeve and outer surface of the column was specified with friction coefficient 0.1. As a result of the analysis, the stress, displacement and contact pressure distribution were obtained.

3. Results of the FEM analyses of the head-punch block with various guides distribution
The example results for the 3N guide configuration are presented in figures 3–5. By analysing the stress distribution in figures 3 we can observe that the peak value of stress occurs at the bottom of the guiding columns and it corresponds with its bending stress. Additionally, the stress concentration is visible nearby the threaded connection which holds the piercing punch and its chunk. If we analyse the deflection of the punch in the direction of the axis (A) we can observe value of 0.275 mm, which is much greater than the single deflection of the head-punch block [24]. The reason for that is significant deflection of the guiding columns, which affects and multiplies the displacement of the point A. The obtained value exceeds the distance between the cutting edges of the punch and the die. However, the transmission ratio of these displacement equals the ratio of the distance between point C (the center of mass of polygon created from the axis of guiding columns) and $A - AC$ and the distance measured from the punch cutting edge and bottom surface of the head-punch block [24]. Since this ratio is lower than 1 it means that the punch deflection will be lower than the point A displacement obtained from

![Figure 2. Construction of FEM model of the head-punch plate of the punching die with guiding system in ABAQUS: $F_p$ – perforation force, $F_{RS}$ – return springs force, $F_{BH}$ – blank holder force, $F_{PP}$ – pressure plate force, $K$ – stiffness of the spring.](image-url)
the FEM analyses. Based on the results, three parameters were determined: maximum bending stress in the guiding column, total deflection in the punch axis (A) and punch deflection. These parameters were further used to evaluate various types of guiding column distribution.

Figure 3. Mises stress distribution $\sigma_{\text{mises}}$ (Pa) on the head-punch plate with 3N guide configuration.

Figure 4. Displacement $f$ (m) in the direction of the punch axis (A) of the head-punch plate with 3N guide configuration.

If we separate the guiding columns and sleeves from the model, the contact pressure distribution on both of these components can be analysed. Due to the symmetry of the model the contact pressure distribution on right (1R) and left (1L) columns and sleeves is identical. The only difference occurs between the columns and sleeves positioned in different rows. We can observe that the value of the contact pressure between the guide parts in the first row (1L or 1R) is greater than the one present for the rear guide (2). For the further analysis, only the most loaded guide components are taken into consideration. For each case the maximum contact pressure for both the column and the sleeve was measured. Additionally, the deflection of the guiding column was tested in order to verify the reasonability of the obtained results.

Figure 5. The contact pressure distribution $p_{\text{con}}$ on the guiding columns (a) and sleeves (top view – b, bottom view – c) for 3N guide configuration.
The values of all the above-mentioned parameters for six chosen types of guiding columns distribution are presented in table 1. As can be observed, increasing the number of guides significantly decreases the contact pressure on both guiding columns and sleeves. This may result in extending the life of the guiding components and in improving the motion smoothness of the punching die during belt perforation. However, the peak value of contact pressure does not exceed the allowable stress for a brass, which in case of the similar designs should be between 10–17 MPa. The same correlation is visible in other parameters aside from mass of the plate \( m \). The mass depends on the overall dimensions necessary to be able to properly distribute all the guides as well as the return springs which should be positioned in the closest neighborhood to achieve the best properties of the designed machine. Basically, increasing the distance between the columns in the horizontal direction will mostly cause the mass increment, which is why the 2H configuration is the heaviest one. Of course, in this configuration the width of the head-punch block could be reduced, but the necessity of connecting different components like carriages of the linear guides or the blank holder to it may prevent it. In order to be able to evaluate different configurations and find the effective solution, it was assumed that the width is constant. Based on the above, the conclusion at first glance is that using more guides will improve the machine performance since we improve strength and stiffness of it. However, it is worth mentioning that increasing the number of guiding columns will increase the costs, complicate the manufacturing process and increase the mass of the whole punching die, which is why it is so important to find the middle-ground solution.

### Table 1. Results of the FEM analyses of the head-punch block with various guides configuration.

| Type of guiding column distribution | Mass of the plate \( m \) (kg) | Max. contact pressure – column \( p_c \) (MPa) | Max. contact pressure – sleeve \( p_s \) (MPa) | Max. bending stress \( \sigma_b \) (MPa) | Total deflection in the punch axis \( f_A \) (mm) | Column deflection \( f_c \) (mm) | Punch deflection \( f_{PN} \) (mm) |
|------------------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------|-------------------------------|-----------------------------|
| 2V                                 | 26.733                          | 11.94                                         | 12.62                                         | 67.5                                          | 0.387                           | 0.106                          | 0.078                       |
| 2H                                 | 31.591                          | 11.64                                         | 12.6                                         | 62.7                                          | 0.403                           | 0.092                          | 0.059                       |
| 3N                                 | 26.432                          | 7.40                                          | 7.84                                         | 42.2                                          | 0.275                           | 0.062                          | 0.048                       |
| 3IN                                | 28.056                          | 8.43                                          | 8.98                                         | 43.3                                          | 0.343                           | 0.066                          | 0.057                       |
| 4R                                 | 27.761                          | 5.87                                          | 6.28                                         | 32.1                                          | 0.227                           | 0.047                          | 0.039                       |
| 4S                                 | 30.999                          | 7.17                                          | 7.62                                         | 34.5                                          | 0.281                           | 0.05                           | 0.044                       |

### 4. Evaluation of different configurations of the guides in the punching die

As was stated in section 3, it is very hard to evaluate different configurations of the guides using only one single criteria. To do so, authors decided to make a comparison of the contact pressure distribution for the cases with the same number of guides and limiting it to the same value of 13 MPa for all cases. The results of these analyses are presented in figures 6–11.

If we compare the results for the configurations with 2 guiding columns (2V – figure 6 and 2H – figure 7), we can observe that in the second case additional contact pressure area inside the sleeve occurs. This has an effect on slightly more uniform stress distribution since it is distributed on the greater area. However, if we compare the results from the table 1, it is obvious that the configuration 2H is characterized with greater stiffness in the punch and columns regions (due to the increase of the \( AC \) distance) and lower bending stress of the column, but the mass of the plate has drastically grown.

The comparison between the configurations with 3 guiding columns (3N – figure 8 and 3IN – figure 9), shows that inverting the triangular distribution of the column worsens all the analysed parameters. Although comparing it to the 2H configuration proves that adding additional guide may reduce the contact pressure and bending stress, but the benefits in the punch deflection do not cover the additional cost of the third set of guiding components. In this case we can also observe an additional region of contact pressure in the solution more adequate for the analysed design of the punching die.
Figure 6. Contact pressure distribution on the guiding column and sleeve for 2V configuration.

Figure 7. Contact pressure distribution on the guiding column and sleeve for 2H configuration.

Figure 8. Contact pressure distribution on the guiding column and sleeve for 3N configuration.
Figure 9. Contact pressure distribution on the guiding column and sleeve for 3IN configuration.

Figure 10. Contact pressure distribution on the guiding column and sleeve for 4R configuration.

Figure 11. Contact pressure distribution on the guiding column and sleeve for 4S configuration.
The additional area of contact pressure is also present in both analysed cases with four guiding columns (4R – figure 10 and 4S – figure 11). Out of these two examples, the rectangular pattern (4R) is characterized by much more advantageous properties than the staggered pattern in all aspects of strength, stiffness and mass. Comparing the 4S configuration with the 3N one we can see a very small improvement in maximum contact pressure or the punch deflection, but the bending stress of the column is reduced by 18%. But since the head-punch block with 4 guides is heavier and supposedly more expensive this solution should not be considered during the design process. On the other hand, the benefits of using four guiding columns distributed in rectangular pattern are clearly visible, with the exception of the increased mass and a more complex construction.

In order to evaluate different configurations of the guides in the punching die, two methods were applied (figure 12). In the first one (figure 12a) the parameter which describes the efficiency of the guiding system and has to be minimized is the relative plate deflection in the A point to the mass of the head-punch block. In this case the positive correlation between the number of guiding columns can be observed and the previously mentioned conclusions are justified. However, this method does not take into consideration all analysed aspects. For that reason a different approach was used in which the evaluation parameter e is introduced as shown in equation (1), in which the results for the simplest 2V guiding configuration is treated as reference values (figure 12b). Because all of the parameters have to be minimized in order to achieve the effective construction of the punching die, this value has to be as low as possible. In that way we are able to take into the consideration multiple factors and evaluate it with a single value. As can be observed, the difference between the 3N and 4R configuration is very small and can be treated as negligible. Since the mass of the punching die also affects the power consumption of its drive system and according to the principals used in machine design the construction should be as simple as possible, it is recommended to use three guides in the normal triangular pattern (3N).

\[
e = \frac{n}{n_{\text{min}}} \cdot \frac{p_{\text{max}}}{p_{\text{max,2V}}} \cdot \frac{f_{PN}}{f_{PN,2V}} \cdot \frac{m}{m_{2V}}
\]

Figure 12. The evaluation of different configurations of the guides in the punching die based on the relative deflection of the plate to plate mass \( f_A / m \) (a) and evaluation parameter \( e \) (b).

5. The influence of the compactness of the guiding columns distribution
The last aspect which was considered in this research is the influence of the compactness of the guiding columns distribution on the punch deflections, maximum column bending stress, punch deflection and contact pressure on the column and the sleeve. The test was performed for 3N guide configuration and the distances between the guiding columns in vertical (\( a \)) and horizontal (\( b \)) direction were the variables. The results for various distances \( a \) in a range of 110–190 mm are presented in table 2 and for various distances \( b \) in the range of 80–160 mm are presented in table 3. In both cases, the increment was set as 20 mm.
Table 2. Results of the FEM analyses of the head-punch block with 3N guide configuration and various distance between columns in vertical direction a.

| Distance a (mm) | Max. contact pressure – column \( p_c \) (MPa) | Max. contact pressure – sleeve \( p_s \) (MPa) | Max. bending stress \( \sigma_b \) (MPa) | Total deflection in the punch axis \( f_A \) (mm) | Column deflection \( f_c \) (mm) | Punch deflection \( f_{PN} \) (mm) |
|----------------|---------------------------------|---------------------------------|-----------------------------|-------------------------------|-----------------|-----------------|
| 110           | 7.41                            | 7.86                            | 42.3                        | 0.275                         | 0.062           | 0.0475          |
| 130           | 7.42                            | 7.86                            | 42.3                        | 0.275                         | 0.062           | 0.0475          |
| 150           | 7.42                            | 7.86                            | 42.3                        | 0.275                         | 0.062           | 0.0475          |
| 170           | 7.40                            | 7.84                            | 42.2                        | 0.276                         | 0.061           | 0.0477          |
| 190           | 7.38                            | 7.82                            | 42.1                        | 0.276                         | 0.061           | 0.0477          |

Table 3. Results of the FEM analyses of the head-punch block with 3N guide configuration and various distance between columns in vertical direction b.

| Distance b (mm) | Mass of the plate \( m \) (kg) | Max. contact pressure – column \( p_c \) (MPa) | Max. contact pressure – sleeve \( p_s \) (MPa) | Max. bending stress \( \sigma_b \) (MPa) | Total deflection in the punch axis \( f_A \) (mm) | Column deflection \( f_c \) (mm) | Punch deflection \( f_{PN} \) (mm) |
|----------------|-------------------------------|---------------------------------|---------------------------------|-----------------------------|-------------------------------|-----------------|-----------------|
| 80            | 25.142                        | 7.36                            | 7.82                            | 42.1                        | 0.275                         | 0.062           | 0.0485          |
| 100           | 26.733                        | 7.40                            | 7.84                            | 42.2                        | 0.275                         | 0.062           | 0.0475          |
| 120           | 27.733                        | 7.46                            | 7.9                             | 42.6                        | 0.277                         | 0.062           | 0.0469          |
| 140           | 29.028                        | 7.53                            | 7.98                            | 42.9                        | 0.279                         | 0.062           | 0.0463          |
| 160           | 30.323                        | 7.61                            | 8.04                            | 43.3                        | 0.28                          | 0.062           | 0.0455          |

Based on the obtained results, no correlation is visible between the distance in the vertical direction and any of the analysed parameters. This means that for the purpose of designing the compact and light constructions of the punching dies, the guiding columns should be spaced as close to each other as possible in this direction.

On the other hand, for the spacing between the columns in horizontal direction some correlations can be found. Although the column deflection, maximum bending stress, total deflection and contact pressure of the head-punch block does not change significantly, the important differences may be observed in the punch deflection and the mass of the plate. By increasing the spacing between the column in the horizontal direction, we are able to increase the stiffness of the construction, which...
results in decreasing the punch deflection as the center of mass of the guiding system is pushed away from the punch axis. This correlation was proven to be linear as is presented in figure 13. Unfortunately, increasing distance $b$ causes the linear mass growth, which is negative. This proves that by changing the spacing of the columns in the horizontal direction we are able to steer the punch deflection and adjust it to the strict requirements for belt perforation at a cost of increasing the weight of the designed construction.

6. Conclusion
The presented analysis proved that the distribution of the guiding columns in the punching die has an effect on multiple aspects of the machine performance, such as stiffness, contact pressure distribution, strength, mass etc. The most important aspect for belt perforation is the possibility of designing the construction which maintains a very small punch-die clearance. As was shown, choosing different configurations of the guiding columns distribution, as well as changing the spacing between columns in the horizontal direction, make it possible to steer the punch deflection and adjust it to meet the specific requirements. However, it is not too easy to properly select the type of configuration and it is necessary to analyse various aspects connected with economy, exploitation parameters and constructional features.

Based on the presented results, we can conclude that adding an extra column or columns to the basic minimal variant of two guides will improve the performance of the punching die. By analysing multiple factors it was proved that using either 3N or 4R configurations provides the best effects for punching dies which are one-sided guided, as the ones used in the belt perforation. The presented research also shows the methodology of modelling similar constructional issues using FEM and how to evaluate various solutions in order to design effective machines.

7. References
[1] Talaśka K and Wojtkowiak D 2018 Modelling mechanical properties of the multilayer composite materials with the polyamide core MATEC Web of Conferences 157 02052
[2] Wojtkowiak D and Talaśka K 2019 The influence of the piercing punch profile on the stress distribution on its cutting edge MATEC Web of Conferences 254 02001
[3] Wojtkowiak D and Talaśka K 2019 Determination of the effective geometrical features of the piercing punch for polymer composite belts Int. J. Adv. Manuf. Technol. 104 315–332
[4] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2018 Estimation of the perforation force for polymer composite conveyor belts taking into consideration the shape of the piercing punch Int. J. Adv. Manuf. Technol. 98 2539–2561
[5] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2018 Analysis of the influence of the cutting edge geometry on parameters of the perforation process for conveyor and transmission belts MATEC Web of Conferences 157 01022
[6] Wilczyński D, Malujda I, Górecki J, Domek G 2019 Experimental research on the process of cutting transport belts MATEC Web of Conferences 254 05014
[7] Wałęsa K, Malujda I and Talaśka K 2018 Butt Welding of Round Drive Belts Acta Mech. et Auto. 12 115–126
[8] Wałęsa K, Malujda I, Górecki J and Wilczyński D 2019 The temperature distribution during heating in hot plate welding process MATEC Web of Conferences 254 02033
[9] Wałęsa K, Mysiukiewicz O, Pietrzak M, Górecki J and Wilczyński D 2019 Preliminary research of the thermomechanical properties of the round drive belts MATEC Web of Conferences 254 06007
[10] Wilczyński D, Berdychowski M, Wojtkowiak D, Górecki J and Wałęsa K 2019 Experimental and numerical tests of the compaction process of loose material in the form of sawdust MATEC Web of Conferences 254 02042
[11] Wilczyński D, Talaśka K, Malujda I, Jankowiak P 2018 Experimental research on biomass cutting process MATEC Web of Conferences 157 07016
[12] Wilczyński D, Malujda I, Talaśka K and Długi R 2017 The Study of Mechanical Properties of Natural Polymers in the Compacting Process Procedia Engineering 177 411–418
[13] Górecki J, Malujda I, Talaśka K, Wilczyński D and Wojtkowiak D 2018 Influence of geometrical parameters of convergent sleeve on the value of limit stress MATEC Web of Conferences 157 05006
[14] Górecki J, Malujda I, and Wilczyński D 2019 The influence of geometrical parameters of the forming channel on the boundary value of the axial force in the agglomeration process of dry ice MATEC Web of Conferences 254 05001
[15] Górecki J, Malujda I, Wilczyński D and Wojtkowiak D 2019 Influence of the face surface shape of the piston on the limit value of compaction stress in the process of dry ice agglomeration MATEC Web of Conferences 254 06001
[16] Kukla M, Talaśka K and Malujda I 2019 Damping in magnetorheological elastomers under compressive stress MATEC Web of Conferences 254 06002
[17] Kukla M, Górecki J, Maluda I, Talaśka K and Tarkowski P 2017 The Determination of Mechanical Properties of Magnetorheological Elastomers (MREs) Procedia Engineering 177 324–330
[18] Shaukharova A, Liang Y, Feng H and Xu B 2016 Study of Stiffness of Linear Guide Pairs by Experiment and FEA World Journal of Engineering and Technology 4 115–128
[19] Yi Y-S, Yoon YK, Choi JS, Yoo J, Lee DJ, Lee SW and Lee SJ 2008 Dynamic analysis of a linear motion guide having rolling elements for precision positioning devices Journal of Mechanical Science and Technology 22 50–60
[20] Jeong J, Kang E and Jeong J 2014 Equivalent stiffness modeling of linear motion guideways for stage systems International Journal of Precision Engineering and Manufacturing 15 1987–1993
[21] Dudziak M, Domek G, Kołodziej A and Talaśka K 2014 Contact problems between the hub and the shaft with a three-angular shape of cross-section for different angular positions Procedia Engineering 96 50–58
[22] Dudziak M, Kołodziej A, Domek G and Talaśka K 2017 Multi-angularity - Identification of parameters and compatibility conditions of the axisymmetric connection with form deviations Procedia Engineering 177 431–438
[23] Abaqus User’s Manual, Version 6.14, Dassault Systèmes Simulia Corp., Providence, Rhode Island, USA 2013
[24] Wojtkowiak D, Talaśka K and Fierek A 2019 (in press) The application of the Finite Element Method analyses in the process of designing the punching die for belt perforation IOP Conference Series: Materials Science and Engineering