Modelling the Belt Perforation Process with the Piercing Punch and the Die in the Context of the Construction of the Punching Dies

D Wojtkowiak and K Talaśka
Chair of Basics of Machine Design, Poznan University of Technology, Piotrowo 3 street, 61-138 Poznań, Poland
dominik.wojtkowiak@put.poznan.pl

Abstract. Proper usage of modelling in the design process should result in achieving the effective construction of the machine. However, the methodology of modelling should be adjusted to the specific application. This paper presents the algorithm of modelling the belt perforation process. Authors show the main aspects that should be taken into consideration during the design process of punching dies. Important correlations between construction, process and exploitation parameters are described along with the analysis methods. The main focus of the paper is put on the geometry of the piercing punch, which can significantly change perforation force, tool life and hole quality when it is modified. The paper also analyses the impact of punch velocity and temperature on the force necessary to pierce the material. Additionally, the methodology of determining the mechanical properties of the belt used for further modelling is discussed.

1. Introduction

Modelling of mechanical systems and processes performed by them may provide a lot of helpful data, which can be further used for the design process of modern machines. The most complex set of useful information can be obtained by using the combination of all three known approaches for modelling: deriving analytical models, performing numerical analysis or computer simulations and performing experimental tests. All these methods can be combined in any possible way, e.g. the model may be derived based on the computer simulations, where the computational model is validated by the experimental results or the numerical analysis may be performed based on the analytical model. Choosing the right method depends on many factors, like the object of research interests, its application, the analysed aspect, etc. This indicates that it cannot be generalized and the proper methodology of modelling should be determined for the specified type of the machines. Since nowadays machines tend to be automated, modelling should be performed in the context of both the construction of the machine or its systems and the steering process of the device. In the presented research, authors have focused on modelling within the context of the construction of punching dies for belt perforation, however the methodology derived by the authors will also provide useful information for the design process of its steering system.

In the paper, authors have presented the methodology of modelling the belt perforation process with the piercing punch and the die. As was proved in the following studies [1-3], this method is the most suitable one for multilayer composite belts and has a lot of potential to be modified in the context of
lowering perforation force, extending tool life and improving hole quality in perforated belts. All these parameters can be modelled in the function of the piercing punch geometry in order to find the effective construction solution. If the combination of these functions is taken into consideration, the optimization of the tool shape may be performed, as presented in [3]. Since the high divergence of the belt’s mechanical properties occur, it is difficult to determine one universal tool for all types of the belt. By using the presented methodology it is possible to design a few sets of tools suitable for various groups of belts. By maintaining the facility of the piercing punch replacement, it is possible to design universal automated machines for belt perforation, which will improve the production process of vacuum conveyor belts.

2. Methodology of modelling belt perforation process

The methodology of modelling the belt perforation process in the context of the construction of the punching dies is presented in figure 1.

![Figure 1. Algorithm of modelling the belt perforation process in the context of the construction of punching dies](image)

It can be observed that in the presented algorithm modelling is used in all stages of designing the machine. At the preliminary stage, mechanical properties of the selected belt type are determined and the decision about designing the tool or selecting the one with specified geometry has to be made. The data obtained in the preliminary stage are used in the elaboration of the detailed technical design. Since the main focus of the research is put on the tool geometry and its influence on perforation force, tool life and hole quality, the majority of modelling occurs at this stage. Depending on the previous decision, modelling can be used either for analysing the above mentioned correlations or applying them in the optimization process to determine the effective shape of the piercing punch. In the next stages, the impact of process parameters like punch velocity or temperature, is analysed and the results are directly used in the design of the drive system. The same method is used for the design of the punching die, in which the results of strength and rigidity analyses are applied in order to achieve the effective construction. Although in the presented algorithm modelling does not cover the stages of manufacturing,
prototype-testing and technical documentation preparation, it does indirectly facilitate all of these processes. The generated 3D models of the machine components necessary for FEM analysis can be used for computer aided manufacturing (CAM) and will speed up the preparation of the working and assembly drawings. Thanks to the computer simulations the number of physical prototypes which have to be analysed can be reduced to a minimum. These prototypes will be used only to verify the results obtained in the modelling process.

Based on the above description, it is visible that modelling may improve the design process and the proper methodology for a selected type of the machine can be useful for engineers. In the following sections authors have presented the main assumptions and examples of the analyses for each stage of the modelling.

3. Determination of the mechanical properties of selected types of belts
The first stage of modelling is to establish the entry data which will be used in the design process of the punching die. Since the properties of multilayer polymer composite belts or fibre-reinforced ones can be extremely different [4], the construction features of the designed device may also be characterized with rather high divergence. This indicates that modelling should be performed for selected types of belts or a single group have to be used as the main one. Although the first solution will make it possible to design the universal machine for belt perforation, it will consume a lot of time to perform all the necessary analysis. For that reason it is advantageous to analyse the range of used materials and select the one which will cause the main issues. With this approach, it is possible to spare some time while still maintaining satisfactory effects for other types of belts.

The methodology for determining mechanical properties for selected types of belts is presented in figure 2. Considering the peak perforation force and tool wear, the most rigid belts with increased strength should be considered as the main one. On the other hand, for the quality of the holes elastic light belts or fibre-reinforced ones will cause more problems during the perforation [1]. At this stage the designer has to decide which of the factors is more important and specify the least possible number of belts which will be taken into consideration or analyses which have to be performed in order to achieve the effective punching die construction.

![Figure 2. Methodology of determining mechanical properties for selected types of belts [4]](image)

4. Determination of the effective geometry of the piercing punch
The next stage of modelling can be performed in two different ways depending on whether the tool geometry is defined or not. If we want to use the tool which is already designed and manufactured, the main focus will be put on experimental tests. Based on their results, the peak perforation force can be determined for the selected group of belts, which can be later used in the design process of the machine drive system. Additionally, the 3D model of the piercing punch can be made using reverse engineering and then the finite element method (FEM) analysis may be performed to estimate the tool life. The results of the modelling can be further used to create the datasheet for the selected tool. To evaluate its properties and efficiency of the perforation with this tool we can use the shape factor \( \beta \), which is the
ratio of the peak perforation force for the modified profile tool to the force obtained with a flat punch. If a proper database of datasheets for various tools is generated by the manufacturers of perforated belts, the selection of the right tool will be much easier for engineers. The example of the analysis for different punch profiles is presented in figure 3. The obtained results as well as the research presented in [2, 5] proved that the most suitable and the most universal shape of the piercing punch is the one with a spherical bowl.

Figure 3. Comparison of experimental characteristics of perforation force in the function of the piercing punch displacement for various punch shapes and the belt TLF7S

In case the geometry of the punch is not specified and should be designed along with the punching die, the methodology of deriving the effective geometrical features of the tools is a combination of all methods of modelling described in the introduction. To derive the correlation between the perforation force and the radius of the spherical bowl \( R \) or the diameter of the punch \( D \), FEM analysis should be used and then the experimental results should verify the computational model. In order to estimate the tool life, the best way is to use the analytical model derived in [3], based on which the correlation between the perforation force to transverse force ratio \( F_P/F_T \) and the punch frictional wear can be found. The evaluation of the hole quality can be performed based on the measurement of hole diameters in both perpendicular directions: longitudinal and transverse, which are punched during experimental tests used for perforation force modelling. Based on the obtained results, quality indicators like hole deviation \( \Delta \) or ovality factor \( \delta \) can be calculated. Quality can also be graded based on the number of hole defects, i.e. pull-out fibres, uneven edges, etc. All these correlations are used to perform the optimization of the punch geometry [3].

The impact of the selected geometrical features of the piercing punch is presented in figure 4. Based on the results, we can conclude that the differences in perforation force for various bowl radiiues can reach 50%, while the punch-die clearance influence does not exceed 10%. This indicates that when deriving the model for force estimation (figure 5a), the clearance may be neglected and a proper radius of the spherical bowl should be selected (figure 5b). The methodology of developing the FEM model along with the example results is presented in figure 6.

Figure 4. Example of the experimental tests results showing the influence of the tool geometry on the perforation force: a) for various bowl radiiues \( R \), b) for various punch-die clearances
5. Determination of the effective parameters of the process
Regardless of whether the punch geometry is specified or has to be designed, the next stage of modelling the belt perforation is to determine the influence of the process parameters on exploitation parameters, i.e. peak perforation force, tool life and hole quality. The most important parameter of the punching process is the velocity of the punch. It has a significant effect on the force necessary to pierce the material, since the dynamics of the process increases with greater velocity. Due to the rheological characteristics of the polymer multilayer composite belts, the dynamic response of the material to the compression generated by the punch varies and affects the peak value of the perforation force. The correlation was proved based on the experimental results and presented in figure 7a.

The tests have shown that although the tendency is kept for different belts, the divergence between the magnitude of the influence may occur. This indicates that a proper analysis of correlation between punch velocity and the above mentioned exploitation parameters should be made. For that purpose, FEM analysis using the J-C material model (as presented in section 5) can also be used. In order to take into consideration the dynamic response of the material, the $d_i$ in the J-C damage model, which is responsible...
for the strain velocity impact, should be set as non-zero value. This approach, along with the
determination of the constant value, will be presented in the authors’ future research papers.

The second parameter which may have some influence on the performance of the punching die and
can be steered in the process is the temperature of the piercing punch. In most technological processes
the increased temperature is the negative effect of the dissipation of the used energy and may affect the
structure or mechanical properties of the machined parts. It is one of the advantages of using the
punching for belt perforation instead of drilling or laser cutting [1]. However, as was proved in [6], an
increasing temperature of the tool in a limited range may also have a positive effect, especially on hole
quality and perforation force. The reason for this phenomenon is softening the material and increased
efficiency of hot cutting. This effect can also be analysed using FEM by detailing the J-C model with
the constant of the material \( d_s \) or it can be tested during a series of experiments as presented in figure
7b.

6. Analysing the construction parameters of the punching die
The last stage in which modelling is used during the punching die design is analysing the construction
parameters of the punching die. In this group we can distinguish a kinematic and dynamic analysis
connected with the drive system of the machine, strength analysis of the main components of the device
and rigidity analysis connected with maintaining a proper alignment between the punch and the die.
Most of them are performed as FEM analysis, in which the previously performed perforation force plays
a role of the loading. Based on the obtained results, a proper drive can be selected or dimensions of the
parts can be calculated. Additionally, mass reduction is possible using the topology optimization of the
construction (mainly of the head-punch and the base-die plates). Since it is very hard to verify the
obtained results, it is advantageous to perform the analysis of the meshing influence, which should
eliminate coarse errors.

7. Summary
The methodology presented in the paper can be used to design more effective constructions of punching
dies. One of the advantages of the presented algorithm is combining all modelling methods (analytical,
simulational and experimental one), which makes it possible to perform an efficient process of design.
As can be observed, a seemingly very simple process of belt punching causes a lot of trouble for
perforated belts manufacturers. With a detailed analysis it is possible to discover the complex nature of
the process and achieve the construction which is even 60-70% more efficient. All these aspects prove
that the presented research provides a lot of useful data, which can be applied by the engineers connected
with the selected branch of industry and should facilitate their work.

References
[1] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2017 Mechanik 12 1138-1142
[2] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2018 Int. J. Adv. Manuf. Technol. 98, 9-12,
2539-2561
[3] Wojtkowiak D and Talaśka K 2019 (in press) Int. J. Adv. Manuf. Technol. doi: 10.1007/s00170-
019-03746-7
[4] Talaśka K and Wojtkowiak D 2018 MATEC Web of Conferences 157 02052
[5] Wojtkowiak D and Talaśka K 2019 MATEC Web of Conferences 254 02001
[6] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2018 MATEC Web of Conferences 157 01022