Journal of
MECHANICAL and ENERGY
ENGINEERING

ISSN: 2544-0780 | e-ISSN:2544-1671
Vol. 6(46) | No. 1 | June 2022 | pp. 13-20
DOI: 10.30464/jmee.2021.6.1.13

MODELING AND NUMERICAL ANALYSIS OF THE PROCESS OF PUNCHING ALUMINUM SHEETS TAKING INTO ACCOUNT PUNCH WEAR

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(Received 21 February 2022, Accepted 23 March 2022)

Abstract: The paper presents a modeling and analysis algorithm as well as the results of simulation tests with the use of FEM of a process of punching aluminum sheets used for casings. In industrial practice, the difficulty lies in the correct selection of punching clearance. In order to predict the effect of clearance on the quality of the edge cut, a numerical model was developed taking into account the geometric and physical nonlinearity with damage. The model makes it possible to simulate all the phases of the cutting process, including the fracture phase, which is of key importance to the formation of the workpiece edge. A new approach of creating a real geometry of the punch edge was presented. The geometries developed take into account the most common defects of the punch cut edges. Owing to this, it is possible to predict the course of the process depending on the type and degree of the wear of the cutting edges of the punch. The results obtained showed that for clearances below the value of a = 0.16 mm, the crack has the shape of a straight line. Clearance values a = 0.16 mm and below allow one to obtain a perpendicular shear area and a considerable width of the smooth cutting zone. As the clearance increases, the width of the cutting zone decreases. Punch wear significantly reduces the smooth zone and it increases perpendicular deviation of cut surface.

Keywords: blanking, FEM, aluminum sheets, blanking clearance, punch wear

1. INTRODUCTION

Punching processes are commonly used in plastic working to cut holes of various shapes in metal materials for the construction of many devices and machines (Fig. 1). They can also be used in the production of furniture elements, machine covers, as well as cars and other vehicle bodywork panels. Current research on methods and the design of waste-free punching equipment and process optimization has led to a significant improvement in the quality of semi-finished products, but it is often not yet sufficient. The main factors influencing the quality of the cut surface obtained include the following: tool shape, cutting speed, friction coefficients, cutting tools clearance, temperature, stress state and material structure [1, 2].

Currently, excessive tool wear is also of a huge concern in the punching process. This is often due to the necessity to process hard-to-deform materials, which increases the cutting forces. Wear depends on factors related to the material punched, the construction and technology of cutting devices (the tools and press) and the parameters of the cutting process [4, 5]. Material-related factors affecting the wear of cutting tools include: material type, thickness, plastic properties, hardness and strength, thermo-chemical treatment, homogeneity, type of surface treatment (etching, phosphating, etc.), surface condition (roughness) and the manufacturing method (hot and cold rolling) [6]. Current requirements in the field of punching processes impose the necessity to conduct complex experimental research and to use possibly precise calculation methods of the process [3, 7]. It is a non-linear process in which fast-changing phenomena occur on various scales [8]. This creates problems and difficulties in developing universal methods of modeling and analyzing the physical phenomena occurring in the contact zones of punching tools and material shaped.

Fig. 1. Example of parts with punched elements (EMET Sp. z o. o.)

The aim of this paper is an analysis of the influence of the punching process conditions on the quality of the cut edge of the product. The case of the punching process with variable punching clearance and different variants of punch cutting edge wear was considered. The current wear `degree of the punch's cutting edge is modeled in the literature as a symmetrical rounding of the edge. In fact, it is especially the abrasive wear of the punch that causes an irregular edge of the punch. The irregular cutting edge of the punch may change the mechanics of cracking the material. Therefore, it will change the cutting edge forming process and affect the width values of the individual zones. In order to perform the task, proprietary applications in the LS-Prepost system with the application of FEM were used. The numerical model developed contains new elements in relation to the current state of knowledge, such as taking into account the influence of the previous treatments on the stress and deformation states, the influence of the strain rate on the yield stress and taking into account the damage of the material. The test results obtained make it possible to acquire knowledge about the physical phenomena occurring in the cutting zone and to predict the quality of the cut edge depending on the nature and degree of the wear of the punch.

2. SIMULATION MODEL OF THE PUNCHING PROCESS

The main problems related to the modeling of the punching process for metal materials concern the correct development of constitutive equations (material model) and the modeling of the material breaking (decohesion) process under the influence of complex load states [10, 11]. While modeling the punching process, the influence of the material processed and the tool as well as the influence of punching conditions were taken into account. Physical modeling of the real object was carried out, which made it possible to build a physical model of the process. The mathematical model consisted of continuous incremental mathematical models: constitutional equations, a contact model, a dynamic model and conditions of uniqueness. An important step was an approximation of the continuous mathematical model using the finite element method and the mathematical modeling of the discrete physical model, leading to discrete incremental mathematical models of the physical model of the punching process.

In computer applications, it was assumed that the process involves a spatial state of stresses and a plane state of displacements and deformations. To solve the problem posed, the central difference method, also known as the explicit integration method, was used. The material cut was the aluminum alloy 6060 T66, the basic physical properties of which are summarized in Table 1. Numerical simulations were performed taking into account the real geometry of the cutting tools (Fig. 2) and the technological parameters of the process.

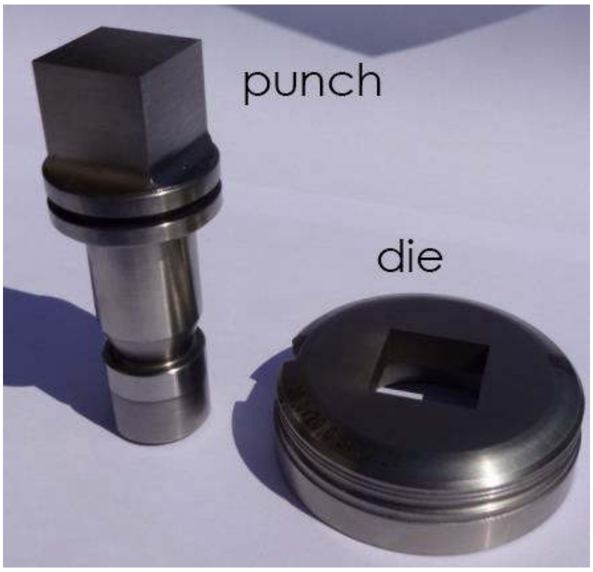

Fig. 2. Cutting tools

The tools were set up as non-deformable bodies. The material thickness was t = 1 mm. The clearance between the punch and the die was variable for each simulation and was in the range of a = 0.1 ÷ 0.35 mm. From the die, translational and rotational degrees of freedom were picked up. The object was discretized with a 2D finite element, type SOLID164. Correct modeling of the material fracture process required a very precise discretization of the sheet model into finite elements, which consisted of 21.000 elements.

The Cowper-Symonds constitutive equation was used to describe the material characteristics of the sheets punched. The aforementioned equation allows one to determine the dependence of plasticizing stresses on plastic deformation, taking into account the cracking (damage) of the material [3].

Tab. 1. Physical properties of the cut material

Density	2.7 g/cm3
Modulus of elasticity - *E*	69500 MPa
Shear modulus - *G*	26100 MPa
Poisson's ratio	0.33
Tensile strength - Rm min.	215 MPa
Yield strength - Rp02 min.	160 MPa
Specific heat at 20°C	898 J/kgK
Thermal expansion coefficient at 20°C	23,4 µm/mK
Elongation min. - A_{50mm}	8 %
Elongation min. - *A*	6 %
Thermal conductivity	209 W/mK
Electrical conductivity	54 %IACS

The simulation model is shown in Figure 3.

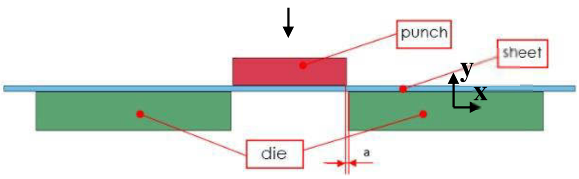

Fig. 3. Simulation model of the punching process

The modeling of the punch wear process took into account its shape changes known as blunting of the cutting edges. The simulation examinations were carried out for various wear variants presented in Figure 4a. Figure 4b shows the mapping of selected cases in the LS-Prepost system.

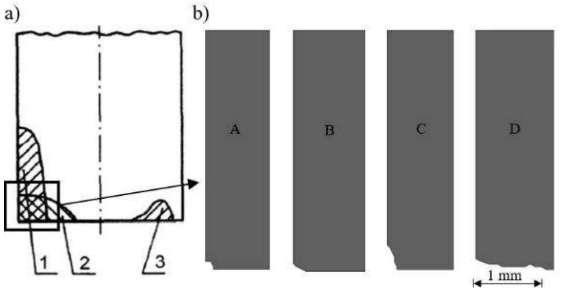

Fig. 4. Blunting of the punch's cutting edges: a) punch wear cases: 1 – side surface wear, 2 – front wear, 3 – other type of frontal wear, e.g. fatigue type [9], b) edge variants mapped in FEM models

3. RESULTS AND DISCUSSION

3.1. Effect of punching clearance

The effect of blanking clearance on the process and the quality of the cut edge was determined for the case of using a punch with sharp cutting edges. Figures 5 - 7 show examples of simulation results in the form of equivalent stresses maps during the material fracture phase and the plate intersection surface view.

In industrial practice, the use of clearances close to zero contributes to a significant increase in cutting forces and accelerates the punch and die cutting edges blunting [13, 14]. Therefore, estimating such a clearance value that at a given sheet thickness will result in obtaining the best possible quality of the cut edge at the acceptable punching forces becomes of key importance. The simulation results show that for clearances below the value of a = 0.16 mm, the crack has the shape of a straight line. For greater values, it has an S shape. Clearance values a = 0.16 mm and below allow one to obtain a perpendicular shear area and a considerable width of the b (smooth) cutting zone (Figs. 5, 7a and b). The use of clearances above a = 0.16 mm facilitates the formation of cracks and material separation. However, it leads to a significant inclination of the cut surface, an increase of the perpendicularity deviation - c and rounding - f, which is undesirable in many cases (Figs. 6, 7c). The clearance value of a = 0.26 mm and above resulted in the product cut surface (Fig. 7c).

Figure 8 shows the clearance value effect on the perpendicularity deviation. Its value increases with an increase of the clearance value. Figure 9 shows the effect of the clearance value on the width of the cut zone on the cut surface. As the clearance increases, the width of the cutting zone decreases.

For the sake of the simulation model validation, the experimental tests were conducted on the Trumpf TruPunch 1000 press located in the facility of the EMET Sp. z o.o. in Szczecinek company (Fig. 10). The experiments were carried out for clearance values a = 0.1 ÷ 0.35 mm with the use of the cutting tools presented in Fig. 2.

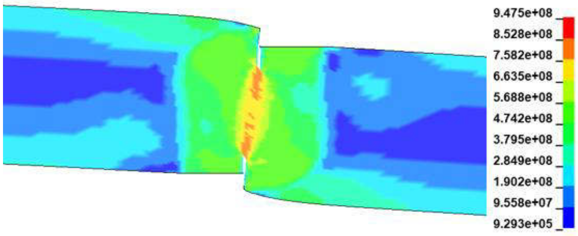

Fig. 5. Equivalent H-M-H stresses during the fracture phase (a = 0.1 mm) [Pa]

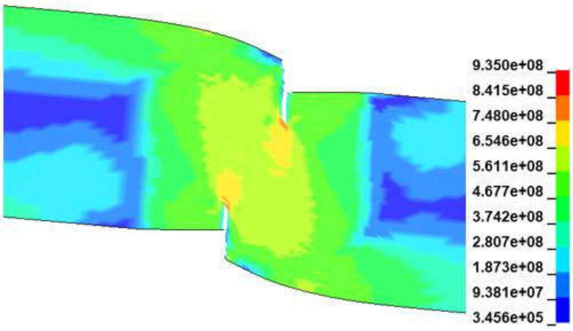

Fig. 6. Equivalent H-M-H stresses during the fracture phase (a = 0.26 mm) [Pa]

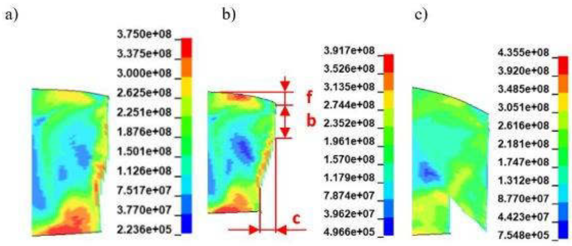

Fig. 7. Equivalent H-M-H stresses after complete separation: a) a = 0.1 mm, b) a = 0.16 mm, c) a = 0.26 mm [Pa]

Comparative analyzes of the cut surface characteristic features showed the compliance of the simulation results with the experiment at the level of about 90% (Fig. 11). In order to increase the accuracy, an analysis of the models sensitivity to the change of the finite element mesh density and their shape needs to be conducted. Such an analysis is planned for the future investigation including creation of 3D models of the cutting process.

3.2. Influence of punch wear

In the actual sources, the punch wear degree in FEM models is defined by the fillet radius. However, there are no analyzes related to the modeling of side wear and frontal wear (Fig. 4b). There is also limited knowledge on the ground of process modeling including fatigue phenomena. The proposed variants are intended to take selected types of wear into account and determine their impact on the cutting mechanisms.

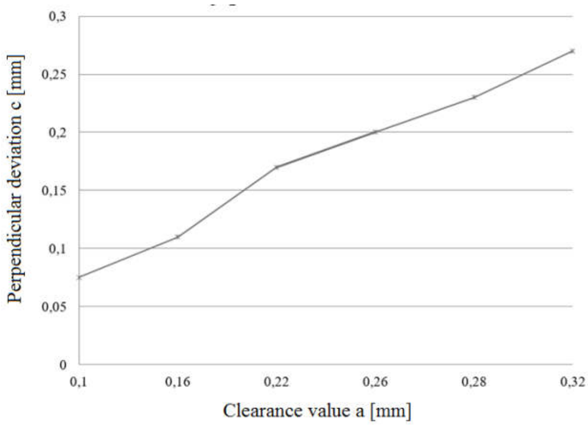

Fig. 8. Influence of the clearance value on the product perpendicularity deviation

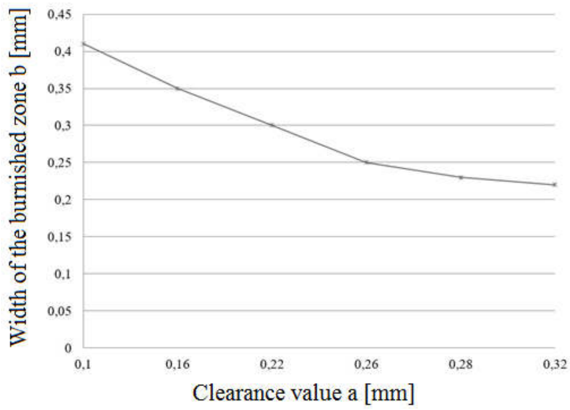

Fig. 9. Influence of the clearance value on the width of the zone burnished

Fig. 10. Test stand in the form of the Trumpf TruPunch 1000 press (EMET Sp.z o.o.)

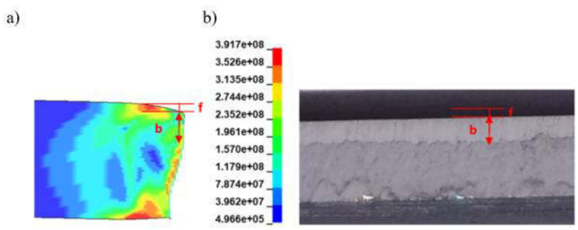

Fig. 11. Cut surface view for a = 0.16 mm: a) FEM simulation, b) experiment

During the plastic flow phase, significant differences in the plasticized area width can be observed. Variant A presented in Fig. 12a causes the concentration of high stress directly under the punch and in the area of the crack that appeared in the early stage of the process near the cutting edge of the die. The variant shown in Figure 12b caused accelerated cracking, which increases the width of the fracture zone on the cut edge. The area of maximum stresses is smaller compared to variant A. The fracture runs along a straight line. The variant shown in Figure 12c causes a cracking process delay which occurs near the cutting edges of the punch and die. A large area of the maximum stress concentration in the cross-section can be noticed. Significant flexing of the material can be observed directly under the punch. Figure 12d shows the plastic flow of the material with no signs of first cracks. The concentration of maximum stresses occurs near the cutting edges of the die. The influence of individual variants on the distribution of equivalent deformations in the cut edge is shown in Figure 13.

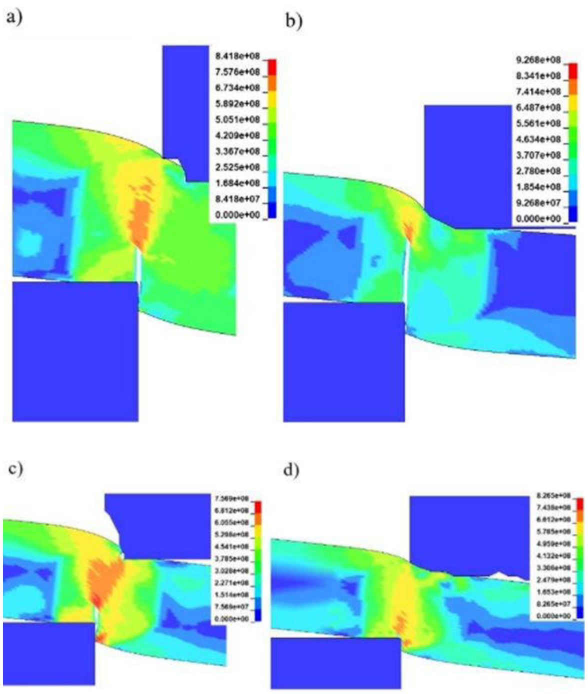

Fig. 12. Equivalent H-M-H stresses during the fracture phase (a = 0.1 mm) for the different punch wear cases

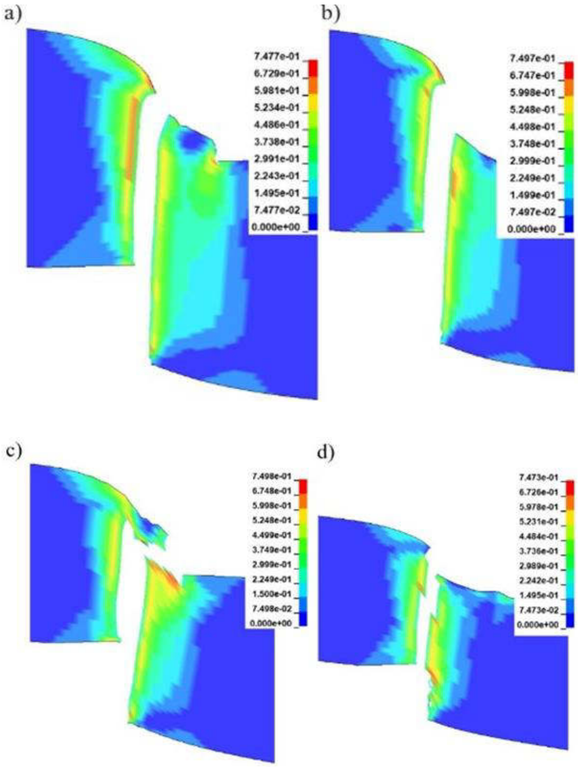

Fig. 13. Equivalent H-M-H stresses after the cutting process (a = 0.1 mm) for different variants of punch wear

Wear type has a significant influence on the areas of maximum deformation and the quality of the cut edge. Variant A (Fig. 13a) resulted in a significant cut edge rounding and characteristic burrs in the upper part of the cross-section. The variant shown in Figure 13b caused the occurrence of similar defects. However, the burr on the removed part is smaller and more gentle. The variant shown in Figure 13c causes damage to the cut edge which is caused by the presence of a characteristic sliver. It also causes a sharp burr on the cut-off part. For variant D (Fig. 13d), a burrs size reduction was observed but, instead, defects in the material cross-section in the form of perpendicularity deviations and damage to the upper edge of the cut-off part of the sheet were observed. Figure 14 shows the influence of the punch wear type on the deformed zone width on the cut-off part. Variants C and D are the most unfavorable cases for which the width of the deformed zone equals to 0.2 and 0.3 mm, respectively.

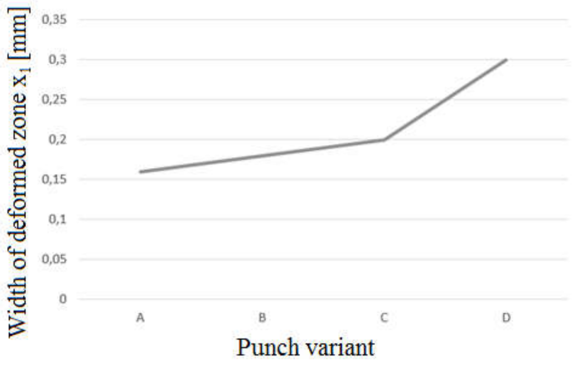

Fig. 14. Influence of punch wear variant on the deformed zone width

4. CONCLUSIONS

Increasing the technological quality of products made of aluminum materials makes it necessary to increase the accuracy of modeling and to perform an analysis of the physical phenomena accompanying the machining process. In the paper, an analysis was conducted of the influence of the punching process conditions on the quality of the cut edge of the product. The following conclusions can be drawn from the analyzes conducted:

1. The models developed in terms of the finite element method taking into account previous treatments on the stress and deformation states, the influence of the strain rate on the yield stress and the damage of the material enable a simulation of all the significant physical phenomena during the cutting process and characteristic features of the cut edge at the level of agreement with the experiment of ca. 90%.
2. The experiments conducted have shown that the appropriate clearance value between the cutting tools can ensure a high quality of the cut edge. The smallest perpendicular deviation can be achieved by applying a punching clearance of ca. a = 10% of sheet thickness t. A clearance value above 15%t has a negative effect on the quality of the cut edge because the perpendicular deviation increases and the width of the smooth zone decreases.
3. For large values of the clearance a = 0.32 mm, the value of the smooth zone width is the smallest, and it amounts to about 20% of the sheet thickness.
4. The wear of the punch side surface causes burrs on the material separation surfaces. Frontal wear causes perpendicularity deviations. The deformation zone was the greatest when the front punch was worn and was equal to x_1 = 0.3 mm.

It is planned to expand 2D FEM models to 3D models in further research. A 3D analysis including the various degrees of tool wear is planned in further examination.

Acknowledgements

The work was created as a result of cooperation with EMET Sp. z o.o. company: a manufacturer of casings and metal elements, Bugno 3, 78-400 Szczecinek.

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Biographical notes

Łukasz Bohdal since 2009, a researcher and lecturer at the Koszalin University of Technology, currently employed as a university professor, conducts basic and applied research in cooperation with business entities. Main specialties: mechanics, designing innovative structures and technologies, modeling, optimization. Author of over 100 scientific publications and one monograph. He completed 4 internships of a research or didactic nature. He has carried out 27 research works of an industrial, implementation and development nature. He participated in consortia and research networks. Co-author of 2 foreign patents. He participated in the implementation of 12 projects as a manager or main contractor.

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Mateusz Miksza received his M.Sc. degree in Mechanics and Machine Design in Machinery Construction and Operation from the Koszalin University of Technology in 2015. Once he graduated, he was employed as a mechanical designer in the field of automotive industry. He started his Ph.D studies in the Doctoral School of the Koszalin University of Technology in 2020. His scientific interests focus on sheet metal bending and metallic materials fatigue life issues. He has published six scientific papers in national journals and book chapters.

Radosław Patyk since 2007, a researcher and lecturer at the Koszalin University of Technology. His research area covers designing innovative structures and technologies with the use of physical, statistical and physical, mathematical and computer modeling methods. His scientific specialty is the processes of surface and volumetric plastic working. He has completed over 50 research and development works for business entities.