The application of Finite Element Method to analysis of states of stresses, strains and displacements during car body elements blanking

Łukasz Bohdal, Leon Kukiełka, Szymon Gontarz, Katarzyna Gotowała

Key words: blanking, modeling, explicit method

Abstract
Finite element modelling provides a great deal of support in understanding technological processes. This paper proposes the application of variational and finite element methods for the analysis of blanking and the nonlinearities of this process. Numerical analysis are conducted in ANSYS LS-Dyna programme, with use of the explicit method. The influence of various process conditions on the strain and stress states and the quality of the final product are analysed.

Introduction

Blanking is the process of forming of the objects which consists in separation of one part of material from the other [2]. Such a separation is accompanied by high plastic strains, which lead to a disturbance of the coherence of the material. In order to cut the material at the required cross section, one has to produce a concentration of strains in this place, which will able to overcome the material coherence. The simplest method to obtaining such a concentration consists in exerting the proper pressure on the surface of the sheet plate by means of two edges. Cutting with punch and die action is one of cutting methods leading to cracking due to tensile stress. Cracking of the material occurs in a weakened cross section, which follows from the previously produced strain [1, 3].

The process of blanking of sheets is a non-linear boundary and initial-value problem. There occur the following nonlinearities in the process: geometric and physical one, as well as nonlinear boundary conditions in the contact area. An analytical solution of this problem is impossible. A numerical solution is possible, however, with the use of the numerical methods and application developed, which enables an analysis of the process at any moment of time, depending of the parameters given of the accepted material model, and for different shapes of the cutting edges. A cold plastic strain of metals results in the occurrence of many phenomena [4-12]. The primary challenge in designing blanking process is developing appropriate design tools and selecting process conditions (e.g., clearance between the punch and die, lubrication method, blanking velocity, punch and die geometry and method of clamping or mounting the sheet metal plates) that will ensure the technical requirements and properties of the resulting product are met. At the same time, it is important to increase the durability of the tools, the efficiency of the process and the quality of the sheared edge, which are all affected by both the material properties and the process parameters.

Modern numerical simulations using the FEM are a considerable asset to mechanical engineering [13-27]. This valuable tool enables both the extension of the time interval and the study of phenomena that must be excluded from experimental research in many cases. It is possible to conduct numerical simulations for even very complex mathematical models and when the boundary conditions are unknown, such as at the tool-sheet contact zones. These contact problems are a fundamental problem in the workplace. Both the complex nature of the phenomena that occur during the contact and the difficulties related to their study drive us to seek new solution methods. Only a limited number of FEM models are currently able to describe the complete blanking process including the complete separation of the material parts through ductile fracturing. Most of the concepts used in the 2D simulation of shearing can be extended to the 3D simulation of blanking. To numerically simulate this process via finite element analysis, a 3D model describing the primary physical phenomena characterizing the mechanical behavior of the metal sheet is required. If 3D modeling can be used to analyze the plastic flow of the material at any time during the process, an evaluation of the sheared edge over the entire length of the metal sheet could be possible.

In this paper, the FEM analysis of blanking is considered using different process parameters. The paper focuses on the development of a methodology to study the phenomena that occur during and after car body elements blanking process (e.g., the change of steady state to unsteady, deformation of the sheet, stress and strain distributions) and analyzing the characteristic features of a sheared edge. Dynamic effects, thermo-mechanical coupling, constitutive damage law and contact friction are taken into account. The yield stress is taken as a function of the strain, the strain rate and the temperature. The damage constitutive law adopted here allows advanced simulations of tool penetration and material separation.

1. Description of blanking process

Blanking is a way to cut sheet (most often in the form of strips or bands), realized with the aid of special devices: blanking dies, usually on power presses (eccentric and crank presses). The material is separated through the action of the cutting edges of the punch and the cutting plane, as a result of an intentionally triggered decohesion process along a certain line (closed or open), known as the shearing line (fig. 1, 2).

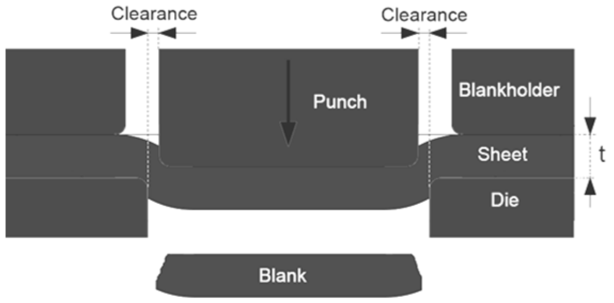


Fig. 1. *Blanking process*

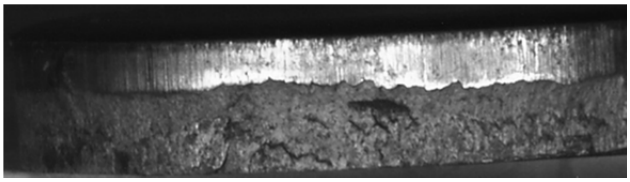


Fig. 2. *Blanking workpiece*

2. Finite element modeling

An analysis of the current literature suggests that the main difficulty in modelling blanking is that only a limited number of FEM models are currently capable of describing the complete shearing process, including the complete separation of the material parts through ductile fracturing. A 3D model describing the primary physical phenomena and characterising the mechanical behaviour of the metal sheet is required to numerically simulate this process using finite element analysis. If 3D modelling used the updated Lagrangian formulation, a FEM that considered process nonlinearity (geometrical, physical), large deformations, strain rate, friction and nonlinear material characteristics could be used to analyse the visco-plastic flow of the material and its stress and strain fields at any time during the blanking process, successfully numerically reproducing the operation. From the perspective of mechanics, the process of blanking metal sheets is treated as a doubly nonlinear boundary-initial problem with a partial knowledge of the boundary conditions. A mathematical description of nonlinear phenomena requires the applications of such rules regarding the formulation of boundary and initial problems, which are different than the rules that are applied in linear problems and more complex solution methods.

The description of the nonlinearity of the material is conducted using an incremental model that takes into account the influence of the history of strains and strain velocities. The object (the metal sheet that is being cut) is treated as a body in which elastic strains may occur (in the scope of reversible strains) together with viscous and plastic strains (in the scope of irreversible strains) with nonlinear strengthening [23]. For the purpose of constructing the material model, the following is used: Huber-Mises-Hencky's nonlinear plasticity condition, the associated flow law and combined strengthening (i.e., isotropic and kinematic). The state of the material after the aforementioned processing is taken into account by introducing the following initial states: displacement, stresses, strains and their velocities. The states of strains and strain rate are described with nonlinear dependences and no linearization. In this description, adequate measures are used for an increment of strains and for an increment of stresses (i.e., an increment of Green-Lagrange strain tensor and an increment of the second symmetric stress tensor of Pioli-Kirchhoff). The incremental contact model covers the contact forces, the contact rigidity, the contact boundary conditions and the friction coefficients in this area. The mathematical model is supplemented with incremental equations of the object's motion and the uniqueness conditions [24, 25]. An incremental function of the total energy of the system is introduced. From the stationary condition of this function, it is possible to derive a variational nonlinear equation to describe the motion and deformation of the object for a typical incremental step. This equation is untangled with spatial discretization using the finite element method, which resulted in discrete systems of equations for the motion and deformation of the object in the blanking process. For the purposes of the solution to the present problem, the central difference method, which is also known as the explicit integration method, is used.

3. Simulation model (2D)

The numerical analysis is a valuable tool which enables the time interval to be expanded, and learning about those phenomena whose experimental research must be excluded. It is possible to conduct a numerical analysis even for very complex mathematical models, also when the boundary conditions are not known, especially in the contact zones. Numerical analyses were conducted with the aid of Ansys/LS – Dyna programme. An element with the overall dimensions of 42 x 5 [mm] placed in the die was subject to an analysis. The diameter of the punch was d = 20 mm, the thickness of the sheet blanked g = 5. Cowper – Symonds' elastic/viscous-plastic material model was accepted for the material blanked. In the model, Hubera – Misesa – Hencky's yield criterion is used together with the associated law of flow [3]. It was assumed that the die and the punch are non-deformable bodies $E \to \infty$. These values were accepted as constant for every simulation.

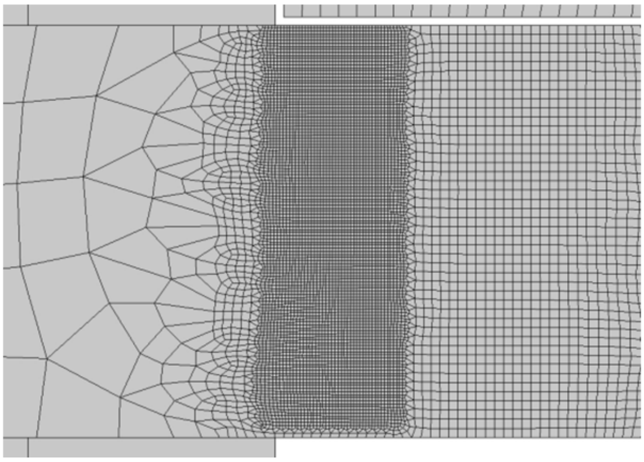


Fig. 3. *Discrete model of blanking (2D)*

The process of cutting with two cutting elements can be divided into a number of characteristic phases:

f) elastic strains,
g) elastic and plastic strains,
h) plastic flow,
i) fracture,
j) a total separation of the object cut from the sheet.

In the phase of elastic strains, the forces exerted on the sheet by the cutting edges of the punch and the die are displaced in relation to one another, and the bending moment occurring as a result of it causes a preliminary bulge of the sheet (figs. 4a and 5a).

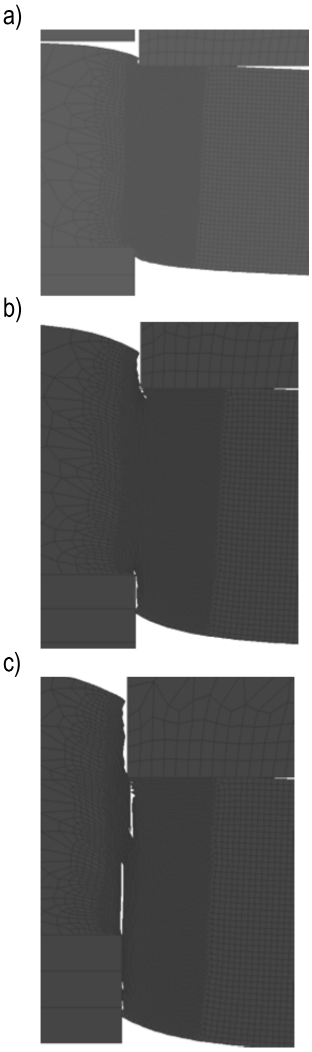
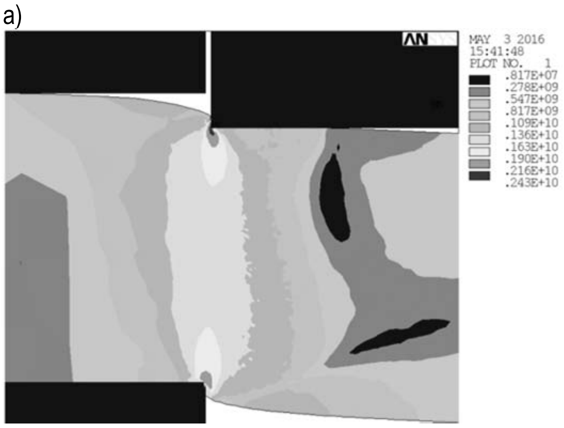


Fig. 4. *Mesh deformation during blanking process: a) elastic and plastic strains, b) plastic flow, c) fracture*



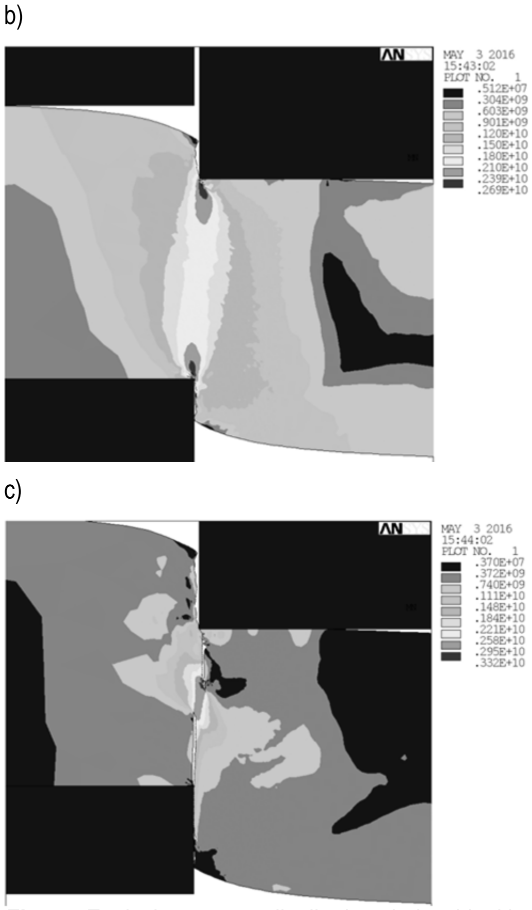


Fig. 5. *Equivalent stress distribution during blanking process: a) elastic and plastic strains, b) plastic flow, c) fracture*

A local plasticization of the material starts the moment the cutting stresses reach the sufficient value. Then the phase of elastic and plastic strains begins (figs. 4b and 5b). The plastic flow phase is characterized by a plastic flow of the material in the neighborhood of the cutting surface. It commences the moment both plastic zones are connected and the plasticized area extends to the whole thickness of the sheet; then there occur conditions which enable the creation of very large plastic strains. When the material is being strengthened, also the cutting stresses increase, which occur on the separation surface. At a certain moment, these stresses may reach a critical value, when the coherence of the material is disturbed (a fracture). The first fracture occur in the places where the material is most deformed, and therefore in the areas of the cutting edges of the die and the punch (figs. 4c and 5c). The fractures going from both edges meet and create a joint fracture zone. Its outline depends on the clearance between the punch and the die. With a greater clearance, the fracture has an S shape. With a minimum clearance, it resembles a straight line. The clearance has a large influence both on the course of the cutting process and on the state of the separation surface. The occurrence of the phase of a total separation of the object cut from the sheet depends mainly of the value of the clearance applied at the blanking. With a large clearance, a total separation of the object occurs as early as at the fracture phase. While observing the surface of the object cut out, one can distinguish the following zones on it [1, 2]:

- a indentation of 1 bottom surface of the sheet in the neighborhood of the place of the cut. It was started in the elastic and plastic phase,
- a glossy and smooth cylindrical surface 2, which occurred in the plastic flow phase,
- a fracture zone 3 titled towards the direction of the cut; it is mat and rough,
- a burr 4 – a sharp projection on the upper sheet surface, running along the edge of the cut (fig. 6).

The height of the burrs which is too big is the result of blanking with an unsuitable clearance, or the result of a rounded (blunted) cutting edge of the tool.

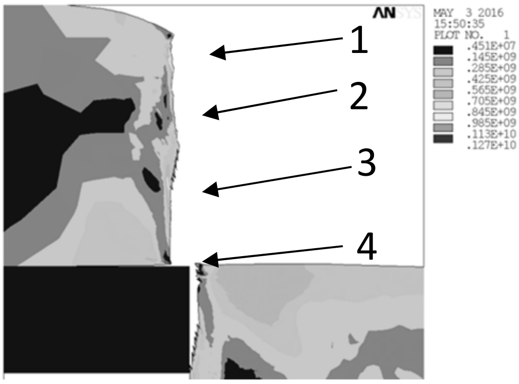
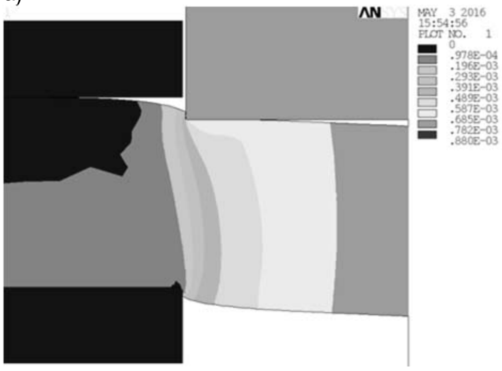


Fig. 6. *Sheared profile*

Figure 7 shows the displacement vector sum. Characteristic bending of workpiece during process can be observed.

a)



b)

c)

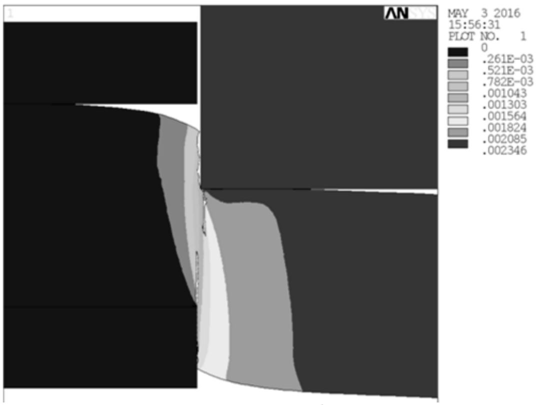
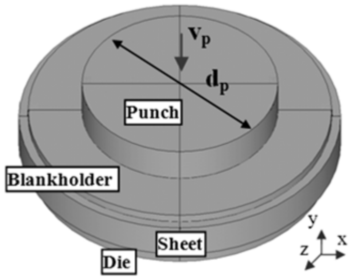


Fig. 7. *Displacement vector sum: a) elastic and plastic strains, b) plastic flow, c) fracture*

4. Simulation model (3D)

A three-dimensional finite element model of blanking is presented in Fig. 8. Numerical calculations are performed for the 3D state of strain and 3D state of stress in this model. 1018 steel is used as the material to be cut in the numerical and experimental studies. A velocity of v_p = 20 mm/s is applied to the punch in the *y* direction. Punch diameter is set about d_p = 22 mm and sheet thickness carry out t = 4 mm. The objects are meshed with an 8-node Solid164 element type with reduced integration and hourglass control, and the mapped mesh is generated with various sheet densities (Fig. 8b). The contact between tools and the deformable sheet metal is described using Coulomb's friction model, and constant coefficients of static friction μ_s = 0,08 and kinetic friction μ_d = 0,009 are accepted. The LS-DYNA contact model „automatic surface to surface" is used in the analysis.

a)



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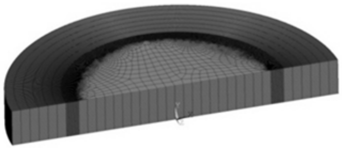

Fig. 8. *3D model of blanking process: a) general view, b) mesh*

A discrete cracking approach was selected to model ductile fracture and element deletion method was adopted to simulate crack propagation. A strain based material separation criterion available with ANSYS LS-Dyna for this material model was used in the simulations. According to this criterion, material separation occurs when the strain value of the leading node is greater than or equal to a limiting value.

During the first part of the blanking process, the punch and die indent the sheet, pulling down some surface material. This causes the sheet to bend over the cutting tools (punch and die), creating the rollover (Fig. 9a). After some punch travel, shear deformation will take over from the indentation, forming the sheared edge of the product. This is generally a smooth surface, which shows some wear due to the contact with the cutting tools. At some point in the shearing phase, ductile material failure will occur in the vicinity of the cutting edge of the punch or die. This fracture propagates through the sheet in the direction of the opposite cutting tool, forming the fractured zone of the product (Fig. 9b). Due to the fracture process, the associated product surface is rougher than the sheared edge.

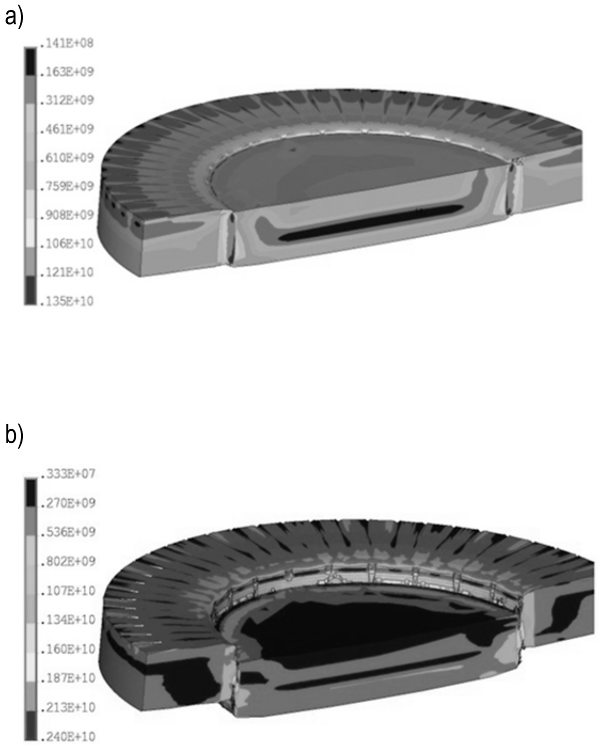

Fig. 9. Equivalent stress distributions: a) plastic flow phase for punch penetration w = 0,5 mm and b) cracking phase for w = 1,7 mm with a constant clearance value c = 0%t

The quality and accuracy of blanked parts can be characterized according to possible defects, including dimensional, positional, form and surface errors include rollover, shear zone, fractured and a burr zone. The simulation results indicate that quality of blanked product can be predicted. The results are in good agreement with those obtained from the experiments, with an approximate error margin of 12%. The blanking clearance can have a great influence upon the shape and dimensional precision of the workpiece. Sample of blanked profiles corresponding to different punch-die clearances are shown in Fig. 10. As can be expected in the case of a large clearance, the profile of the workpiece boundary causes a bad quality due to the presence of large rollover and longer fractured zone.

Fig. 10. *Comparison of simulation workpiece profile with experimental*

On figure 11 the 3D modeling of the auto body sheet blanking with regarding curvilinear shearing line is presented. In order to reduce the computing time material was discretized by using SHELL Element type with Belytschko-Tsay formula.

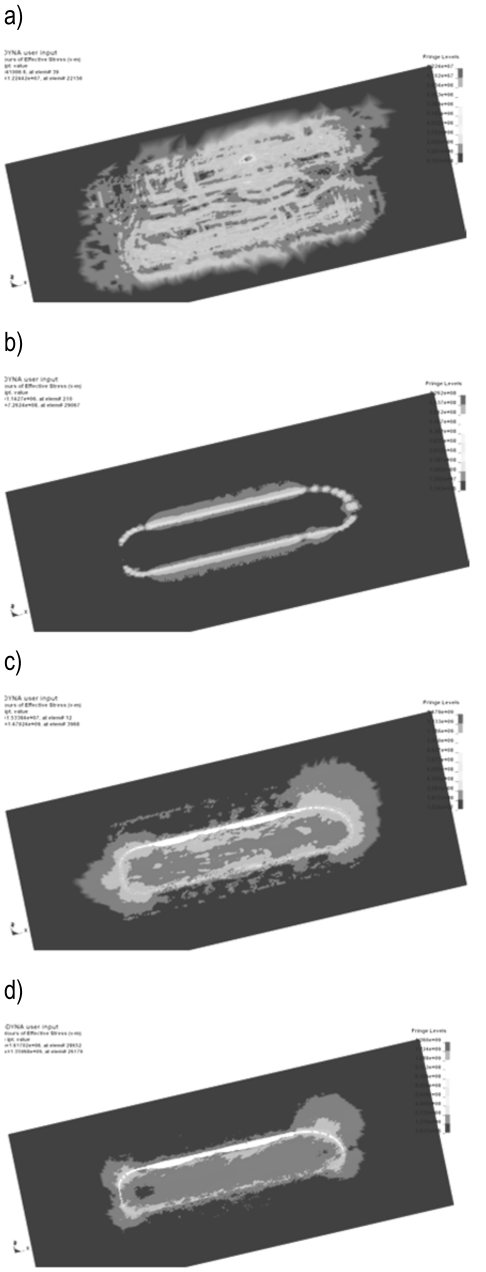

Fig. 11. *Blanking process of curvilinear shearing line element: a) elastic and plastic strains, b) plastic flow, c, d) fracture (equivalent stress distribution)*

a)

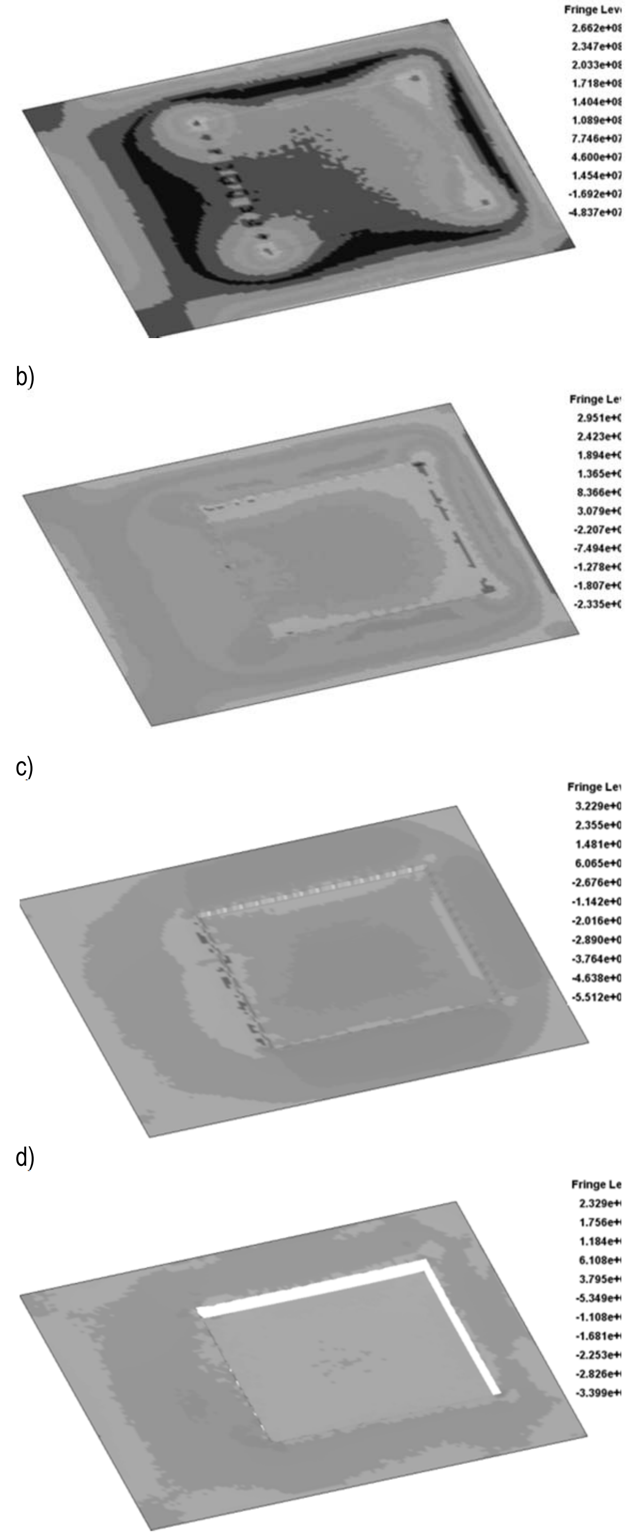

Fig. 12. *Blanking process of curvilinear shearing line element: a) elastic and plastic strains, b) plastic flow, c, d) fracture (contours of pressure)*

Conclusions

The developed numerical investigation of the sheet metal blanking process makes it possible to study the effects of the interaction between the process parameters on the variation of geometry sheared edge. The advanced constitutive models were used to simulate the states of strains, stresses and displacement of material at any time. Owing to the application of state-of-the-art modeling methods, it is possible to analyse the process at any moment of time, to foresee the quality of the surface of the cut, and the product's quality. The results can be used in designing of car elements cutting process for simple and curvilinear shearing line elements.

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Autor:
Dr inż. **Łukasz Bohdal** – Politechnika Koszalińska

Zastosowanie Metody Elementów Skończonych do analizy stanów naprężeń, odkształceń oraz przemieszczeń blach karoseryjnych kształtowanych za pomocą technologii wykrawania

Metoda Elementów Skończonych jest obecnie szeroko wykorzystywana do analizy procesów technologicznych. Praca przedstawia zastosowanie rachunku wariacyjnego i MES do analizy procesu wykrawania z uwzględnieniem nieliniowości procesu. Analizy numeryczne przeprowadzono w systemie ANSYS LS – Dyna z wykorzystaniem metody explicit. Przedstawiono wpływ wybranych warunków realizacji procesu na stany naprężeń, odkształceń i przemieszczeń oraz na jakość wyrobu finalnego.

Słowa kluczowe: wykrawanie, modelowanie, metoda explicit.