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High-speed blanking of copper alloy sheets: Material modeling and simulation

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Abstract. To optimize the blanking process of thin copper sheets (≈ 1 mm thickness), it is necessary to study the influence of the process parameters such as the punch-die clearance and the wear of the punch and the die. For high stroke rates, the strain rate developed in the work-piece can be very high. Therefore, the material modeling must include the dynamic effects. For the modeling part, we propose an elastic-viscoplastic material model combined with a non-linear isotropic damage evolution law based on the theory of the continuum damage mechanics. Our proposed modeling is valid for a wide range of strain rates and temperatures. Finite Element simulations, using the commercial code ABAQUS/Explicit, of the blanking process are then conducted and the results are compared to the experimental investigations. The predicted cut edge of the blanked part and the punch-force displacement curves are discussed as function of the process parameters. The evolution of the shape errors (roll-over depth, fracture depth, shearing depth, and burr formation) as function of the punch-die clearance, the punch and the die wear, and the contact punch/die/blank-holder are presented. A discussion on the different stages of the blanking process as function of the processing parameters is given. The predicted results of the blanking dependence on strain-rate and temperature using our modeling are presented (for the plasticity and damage). The comparison our model results with the experimental ones shows a good agreement.

1. INTRODUCTION

For a large number of metal forming processes and impact applications, the loading conditions are so severe. The resulting profile depends on several parameters: punch-die clearance Cl (defined as $(D_m - D_p)/t$ where D_m and D_p are respectively the die and the punch diameters, and t is the sheet thickness), the punch and the die wear, and the contact between the punch die and the blank-holder. For example, during the high-speed blanking process the quality of the blank is related to the shape of the blanked edge. Four shape errors can be distinguished: the roll-over, the fracture zone (the fracture propagates through the sheet), the burr and the fracture angle (depends mainly on the locus of the crack initiation). Other parameters are known to influence the shape of the product as the sheet thickness, the material properties, and the stroke rates... As mentioned by Poizat et al. [1] in the shearing zone, the strain rates can reach several 1000 s^{-1} . According to Kalpakjian [2] the shear zone is affected by the temperature till several $100 \text{ }^\circ\text{K}$. Therefore, it is necessary to develop robust tools to predict structural response of metals under these loading conditions. In this work, we present some numerical simulations for the blanking based on a new constitutive model for plasticity and damage.

2. MODELING

2.1 Semi-empirical plasticity model

Follansbee and Kocks [3] have presented a detailed description of the deformation of 40 μm grain sized OFE copper in terms of thermally activated flow. This work is based on an internal state-structure variable that describes the physical property of work hardening that occurs as a metallic specimen deforms plasticity. Like in the mechanical threshold stress (MTS) model of Follansbee and Kocks [3], the equivalent von Mises flow stress is written as the sum of the flow stress contributions: a temperature-independent stress $\hat{\sigma}_{ath}$ and a state variable σ_e which evolves with deformation to model hardening (thermally activated processes).

For copper, the Mises flow stress is given by

$$\sigma_{eq} = \hat{\sigma}_{ath} + \sigma_e = \hat{\sigma}_{ath} + \hat{\sigma}_e \left[1 - \left(\frac{k_b T}{\mu b^3 g_0} \cdot \ln \left(\frac{\dot{\epsilon}_0}{\dot{\epsilon}_{eq}^p} \right) \right)^{1/q} \right]^{1/p} \quad (1)$$

where $\hat{\sigma}_e$ represents the mechanical threshold stress for the thermally activated deformation process (yield stress in a reference state at 0 K), g_0 is a normalized activation energy, b is the Burgers vector, k_b is the Boltzmann's constant, μ is the shear modulus, $\dot{\epsilon}_0$ is the reference strain rate and $\dot{\epsilon}_{eq}^p$ is the equivalent plastic rate. The constants $0 \leq p \leq 1$ and $1 \leq q \leq 2$ are empirical constants related to the activation barrier by the thermal component of the applied stress.

Phenomenologically, the athermal deformation processes primarily consider the grain boundary strengthening contributions (Hall-Petch effect) and the thermally activated processes include dislocations interactions with solute atoms and dislocations interactions with other dislocations [4]. The term σ_e is a product of $\hat{\sigma}_e$ and a scaling factor, which is comprise between 0 and 1 and is derives from an Arrhenius expression.

For a given material, the temperature-independent stress is assumed constant, so that we can write the following expression of the macroscopic strain-hardening rate:

$$\theta = \frac{d\hat{\sigma}}{d\dot{\epsilon}_{eq}^p} = \frac{d\hat{\sigma}_e}{d\dot{\epsilon}_{eq}^p} \quad (2)$$

We suggested the following form for the mechanical threshold stress for the thermally activated deformation process

$$\hat{\sigma}_e = \frac{\theta}{\theta_0} \left[\sigma_{eq}^{qs}(\dot{\epsilon}_{eq}^p, \rho_{max}) - \hat{\sigma}_{ath} \right] \quad (3)$$

where θ_0 refers to the initial dynamic stage of strain-hardening rate, $\sigma_{eq}^{qs}(\dot{\epsilon}_{eq}^p, \rho_{max})$ is the quasi-static von Mises flow stress proposed by Kovács and Vörös [5] which evolves with the equivalent plastic deformation $\dot{\epsilon}_{eq}^p$ and to the maximum dislocation density ρ_{max} . The macroscopic strain hardening-rate θ is described by the proposed following form:

$$\theta = \left[\theta_0 + a_2 \ln \left(\dot{\epsilon}_{eq}^p \right) + a_3 \sqrt{\dot{\epsilon}_{eq}^p} \right] \left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}} \right)^m \right] \quad (4)$$

where T_{ref} is a reference temperature, T_{melt} is the melting temperature, m is a softening exponent, a_2 and a_3 are model constants. The expression in the second set of brackets (equation 4) is proposed by Johnson and Cook [6] to describe the dependence of the von Mises flow stress on temperature.

2.2 Isotropic damage model and rupture criterion

The damage model coupled with the proposed plasticity model is based on Continuum Damage Mechanics which defines damage in terms of internal state variable theory and relates the state of

damage in a structural component to globally measurable quantities. Based on our new ductile damage dissipation [7] we propose a nonlinear isotropic model valid for a wide range of strain rates and low homologous temperature ($T < 0.5 \times T_{\text{melt}}$):

$$D = D_i + (D_{cr} - D_i) \left[\frac{\int_{p_{th}}^{\varepsilon_{eq}^p} [\sigma_{eq}]^2 d\varepsilon_{eq}^p}{\int_{p_{th}}^{p_{cr}} [\sigma_{eq}]^2 d\varepsilon_{eq}^p} \right]^K \quad \begin{array}{l} \text{if } \varepsilon_{eq}^p < p_{th} \\ \text{if } p_{th} \leq \varepsilon_{eq}^p \leq p_{cr} \\ \text{if } \varepsilon_{eq}^p > p_{cr} \end{array} \quad (5)$$

where D_{cr} is the critical damage at failure, D_i is the initial damage, K is a non-linear damage exponent. p_{th} and p_{cr} are the threshold and failure equivalent strains which are taken as function of strain rate, temperature and tri-axiality factor [7].

3. FINITE ELEMENT SIMULATION OF THE HIGH SPEED BLANKING PROCESS

3.1 Numerical considerations and experimental setup

The models are implemented in the commercial Finite Element code ABAQUS (Explicit time integration scheme [8]) via a user material subroutine (VUMAT). The sheet is meshed with CPE4R plain strain elements with reduced integration and hourglass control. In the shearing zone, the size of the elements is approximately $10 \mu\text{m}$. Die, blank-holder and punch are analytical rigid surfaces. The friction law used is a Coulomb friction law with a coefficient of 0.02 which is representative of a very good lubrication between the tools and the sheet. The coupling of plasticity and damage is released following the work of Saanouni et al. [9]. The failure initiation and the propagation are controlled by the element deletion. The wear is modelled by taking the tools radii.

To confirm the FEM simulations results blanking experiment were conducted on a 25 T Bruderer press. The cutting tool is a square of $3.51 \text{ mm} \times 3.51 \text{ mm}$. Piezo-electric in-die load sensors are installed directly within the tooling to measure the blanking force and punch penetration where it occurs. The thin sheet is a copper alloy which the thickness is 0.58 mm .

3.2 Experimental validation

In this study, the punch and die radii are equal to $50 \mu\text{m}$ and the punch-die clearance is equal to 8%. A comparison between the results obtained with FEM code ABAQUS and those obtained by experiments (with a Scanning Electron Microscope) can be seen in figure 1. The numerical profile of the blanked part edge is in a good agreement with the experiment profile. The similarity between the profiles (ratio between measured and simulated values) is equal to 66% for the roll-over zone, 101% for the shearing zone, 108% for the fracture zone and 115% for the burr (Figure 1a).

During sheet metal blanking operation, the thin sheet is subjected to more complex solicitations as damage, hardening and initiation and propagation of cracks leading to final rupture. The modeling of blanking is difficult due to the difficulty of describing the different stages of the complete shearing process ending to the separation of the sheet with the workpiece. In figure 1b, the relative punch force¹ vs. relative punch displacement² curve for the studied model are given for a high stroke rate and compared with experimental data. Results obtained with the proposed model are in relative good agreement with experimental curve. The numerical results compared with the experimental ones

¹ The relative punch force is defined as the ratio between the punch force and the maximal experimental punch force.

² The relative punch displacement is defined as the ratio between the punch displacement and the sheet thickness.

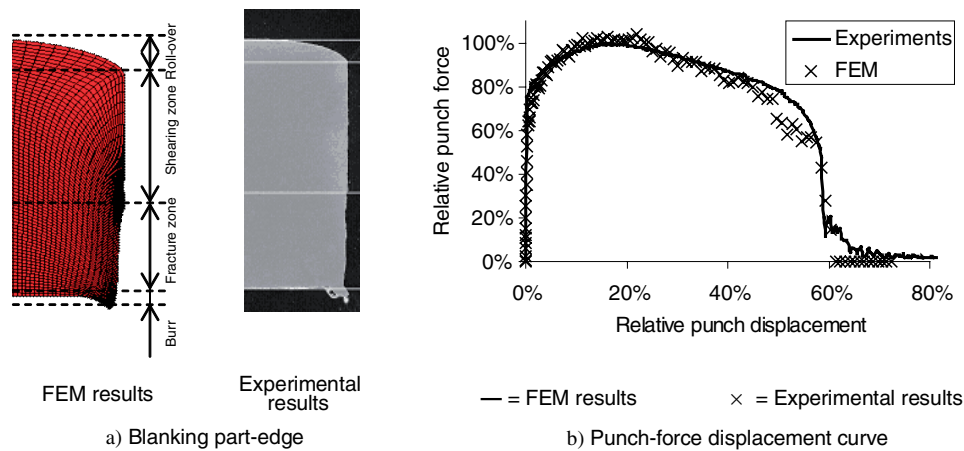


Figure 1. Comparison FEM results and experiments.

(Figures 1a and b) show the reliability of the finite element approach using the proposed plasticity and damage models in the case of high speed blanking process.

3.3 Numerical prediction of the effects of processing parameters

In high speed metal blanking process, the tools wear plays an essential role. Wear is defined as a slow degradation of the tools caused by friction involved between the tool (punch and die) and metal sheet. Equally, the punch-die clearance influences the life of the die and the punch and the metal flow. In this part, we realized a numerical study for the effect of clearance and tools wear on the blanking part edge. Figure 2 shows the effect of the working conditions on the profile for various punch-die clearances (small and large punch-die clearance corresponding respectively to $15 \mu\text{m}$ and $60 \mu\text{m}$) and for various tools wear (sharp tools and dull tools corresponding respectively to $R_p = R_d = 10 \mu\text{m}$ and $R_p = R_d = 75 \mu\text{m}$).

In figures 2, it can also be seen from the simulation results that, when the tools wear is important, the burr appear and the shearing zone increases. Similarly, it can be seen that the fracture angle and the roll over increases as punch-die clearance increases.

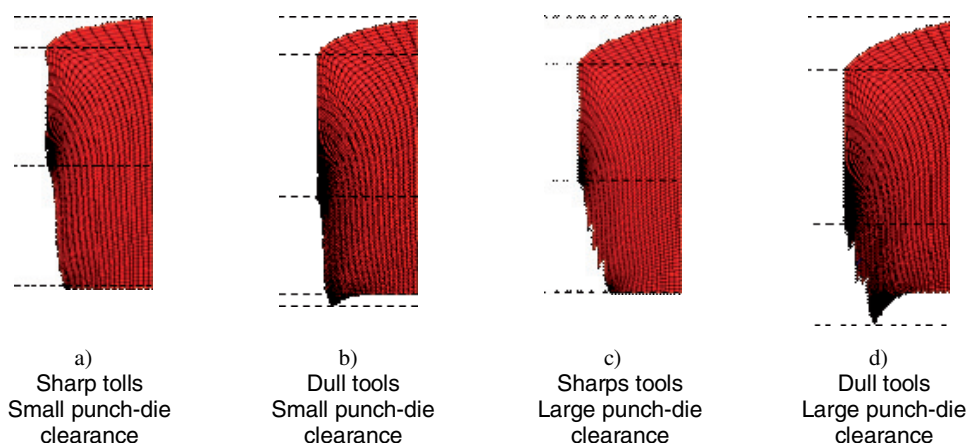


Figure 2. Process parameters effect on the FEM blanked part edge.

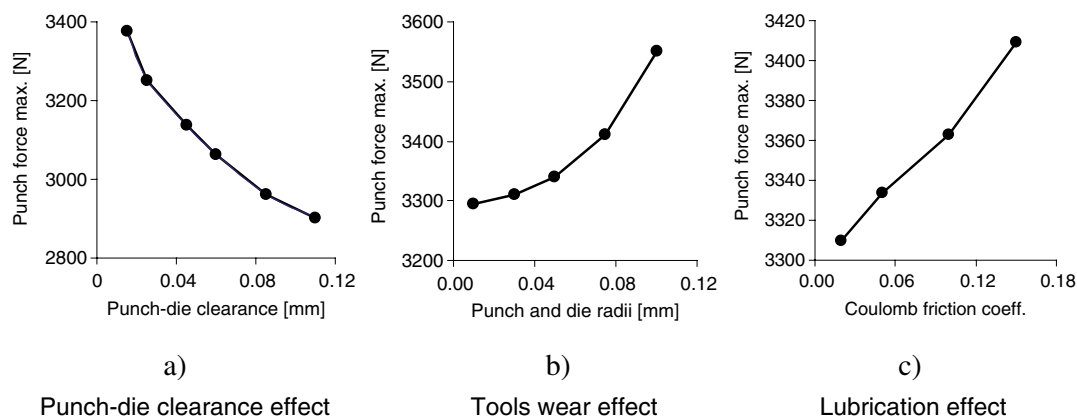


Figure 3. Process parameters effect on the maximum punch force evolution.

We realized a numerical study for the effect of punch-die clearance and tools wear on the blanking part edge (roll-over depth, shearing depth, fracture depth, burr and fracture angle). It is seen that the roll-over and shearing depths increased with the punch-die clearance. Conversely, the fracture depth decreased with clearance. When the punch and die radius increase the rollover depth, the shearing depth, the burr depth and the fracture angle increase. However the fracture depth decreases.

Punching force changes during the high speed blanking process as function of the punch-die clearance, the tools wear and the interface between the tools and the sheet. The slope of the tangent to the force-displacement curves indicates that the crack growth speed is more important for sharp tools. In the same way, the punch penetration is more important for tools wear and for large punch-die clearance. It is seen that the penetration depth at crack initiation results from the flow of the material in the shearing zone. For dull tools, shearing process is dominant during blanking. Our numerical results are qualitatively in good agreement with the empirical knowledge of the influence of the tool wear on the blank profile.

In the industry, users decide which press to use according to the maximum blanking loads. Example of effect of tools wear, punch-die clearance and interface punch / die / blank-holder on the maximum blanking loads is shown in figure 3. When the wear is important the maximum blanking force increase and conversely when for the punch-die clearance increase. It can be seen that the punch-force decrease with the lubrication (Figure 3c). This result is of importance for the press design.

4. CONCLUSIONS

Numerical simulations of the high speed blanking process of a copper alloy sheet have been developed using an elastic-viscoplastic material model (semi-empirical approach) combined with a non-linear isotropic damage evolution law based on the CDM theory. Some significant aspects of finite element simulations of the blanking process are discussed. The comparative study between the experimental results and the numerical ones obtained with ABAQUS (Explicit scheme) shows a good agreement for the blanking part edge and for the punch force evolution.

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