C. R. Mecanique ••• (••••) •••–•••

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Computational modeling of material forming processes / Simulation numérique des procédés de mise en forme

Modelling of the blanking process of high-carbon steel using Lemaitre damage model

Kerim Isik [a,*], Yoshinori Yoshida [b], Lin Chen [c], Till Clausmeyer [a], A. Erman Tekkaya [a]

[a] *Institute of Forming Technology and Lightweight Components, TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany*
[b] *Center for Advanced Die Engineering and Technology (G-CADET), Gifu University, 1-1 Yanagido, 501-1193 Gifu, Japan*
[c] *CW Bearing GmbH, Am Neumarkt 34/36, 22041 Hamburg, Germany*

ARTICLE INFO

Article history:
Received 29 August 2017
Accepted 9 April 2018
Available online xxxx

Keywords:
Damage model
Parameter identification
Blanking
Shear fracture

ABSTRACT

This paper presents a methodology to model a blanking process using a continuum mechanical damage model. A variant of the Lemaitre model, in which the quasi-unilateral conditions are taken into consideration to modify the damage behavior under compressive stress states, is selected as material model. S45C high-carbon steel is analyzed experimentally. To characterize the damage behavior of the material, notched round bar tensile tests with three different notch radii (6 mm, 10 mm, and 20 mm) using image analysis are performed. Using digital image processing, the strain at the deformation zone can be computed for the load–strain curves. Those curves are used as an objective function to determine the parameters of the Lemaitre damage model. The experimental results are compared with the results of the FE analysis of the tensile test. The identified model parameters are used in numerical investigations of axisymmetric blanking. The effect of the model's extension to quasi-unilateral damage evolution is discussed. The crack progress in high-carbon steel sheet during blanking and the final sheared part morphology are predicted and compared with the experimental results. Sheared surface and burr height obtained by the analysis coincide with the results of the blanking experiment.

1. Introduction

Shear-cutting processes require separation of the material from the remaining workpiece. There are various shear-cutting operations such as blanking, trimming, guillotining, punching, and adiabatic shearing, each of which has a certain experimental setup and a set of process parameters. Plastic flow, fracture behavior (material properties) and friction (process parameters) influence the resulting fracture's surface properties [1]. To minimize the efforts for the process design, the predictions of surface quality and required maximum force by cutting machine are mandatory. Especially for sheet metal cutting operations, there are several analytical models to predict the required maximal shearing force and the fraction of sheared and fracture surface to assign the sheared surface quality [2,3]. Application of finite element models using damage models ease and improve these predictions. Hambli [4] used the Lemaitre damage model [5] to simulate fine blanking

---

* Corresponding author.
E-mail addresses: kerim.isik@iul.tu-dortmund.de (K. Isik), yyoshida@gifu-u.ac.jp (Y. Yoshida), chen.15@gmx.de (L. Chen), till.clausmeyer@iul.tu-dortmund.de (T. Clausmeyer), erman.tekkaya@iul.tu-dortmund.de (A. Erman Tekkaya).

https://doi.org/10.1016/j.crme.2018.05.003
1631-0721/

Please cite this article in press as: K. Isik et al., Modelling of the blanking process of high-carbon steel using Lemaitre damage model, C. R. Mecanique (2018), https://doi.org/10.1016/j.crme.2018.05.003

Table 1
Some application examples for Lemaitre model and its variants.

Study	Model specification	Test for characterization	Process
Hambli [4]	Isotropic standard model	Tensile test	Sheet fine blanking
Hambli [7]	Isotropic standard model	Tensile test	Sheet blanking
Gutknecht et al. [10]	Crack-closure enhancement	Notched tensile test In-plane shear test	Sheet blanking
Bouchard et al. [11]	Crack-closure enhancement	Notched tensile test	Cold forging, extrusion

(1% clearance) and showed that the Lemaitre Model is incapable to model the fine blanking process of 4-mm-thick sheets. Hambli [4] suggested that the application of Rice and Tracey's model [6] provides better prediction for crack initiation and propagation. On the contrary, Hambli [7] showed that the Lemaitre model provides better prediction for the blanking process (10% clearance), compared to the Gurson Model [8] for a relatively thick sheet (3.5 mm in sheet thickness). In this study, the predictive capability of a variant of the Lemaitre model is investigated with a moderately thick workpiece (thickness of 1.2 mm). In further studies, the Lemaitre model and its variants are used to model the onset of fracture (Table 1). The most common enhancement of the Lemaitre model is related to the effect of the compressive stress states, crack-closure phenomenon presented in [9]. For the cutting process, especially the studies are concentrating on the sheet metals (as in the studies of Hambli [4] and [7] and Gutknecht et al. [10]). Bouchard et al. investigated the application of the Lemaitre model with crack-closure for more classic bulk forming operations such as cold forging and extrusion [11]. In this work, blanking of a bulk material is investigated. The specimens are cut from bulk material.

In general, material anisotropy is more critical for sheet materials than for bulk ones, because of texture due to the preforming procedure (rolling, etc.). The cutting operations take place in the through-thickness direction, which is not directly related to the planar anisotropy of the sheet. From this point of view, the cutting operation is not a typical sheet forming operation, during which in-plane plane-stress conditions are dominant.

In this paper, the blanking process for a bulk material is modeled using a variant of the Lemaitre model, which is extended to unilateral damage evolution to distinguish damage accumulation for tensile and compressive stress states [9]. The details of this damage model are presented in Section 2. The experimental procedures for material characterization and blanking experiments are explained in Section 3. Section 4 includes the details of finite element simulations of the characterization and blanking tests. The simulation results and comparisons with experiments are discussed in Section 5 and, finally, conclusions are drawn in Section 6.

2. Lemaitre model with a quasi-unilateral damage evolution

2.1. General framework

In the Lemaitre model family, the material deterioration is measured by the damage variable D. More specifically, D stands for the phenomenological construct, which is a measure for homogenized microvoids and microcracks in the material. The limits are $D = 0$ for undamaged material and $D = D_{\text{critical}}$ for the complete material deterioration.

The Lemaitre model according to [12] belongs to the class of thermo-dynamically consistent models. Here thermo-dynamically consistency means that the dissipation

$$0 \le \Omega = \mathbf{T} : \dot{\mathbf{E}} - \dot{\Psi} \tag{1}$$

is always non-negative. $\mathbf{T}$ is an arbitrary stress tensor and $\mathbf{E}$ the thermo-dynamically conjugate strain tensor. In (1), ":" denotes the double contraction product.

$$\Psi = \Psi(\boldsymbol{\chi}) \quad \text{with } \boldsymbol{\chi} = \left\{\mathbf{E}^{\text{e}}, \alpha, D, T_{\text{temp}}\right\}^{\mathsf{T}} \tag{2}$$

represents the Helmholtz free energy, a positive and convex function with respect to its argument $\boldsymbol{\chi}$. The superscript "T" denotes the transpose of a vector or tensor. In the case of the Lemaitre model, common choices for $\boldsymbol{\chi}$ are $\mathbf{E}^{\text{e}}$ for the elastic part of the strain tensor, D for the scalar damage variable, α for the scalar isotropic hardening variable, and T_{temp} for the temperature. Here, the fact that the plastic part $\mathbf{E}^{\text{p}}$ of the total strain $\mathbf{E}$ does not modify the stored or reversible energy is exploited. One obtains $\mathbf{T} = \partial_{\mathbf{E}^{\text{e}}} \Psi$ from (1), where $\partial_{\circ}(\bullet)$ denotes $\partial(\bullet)/\partial_{\circ}$. Similar stress-like driving forces q and Y are given by

$$\begin{aligned} q &= \partial_{\alpha} \Psi(\mathbf{E}^{\text{e}}, \alpha, D, T_{\text{temp}}) \\ Y &= -\partial_{D} \Psi(\mathbf{E}^{\text{e}}, \alpha, D, T_{\text{temp}}) \\ s &= \partial_{T_{\text{temp}}} \Psi(\mathbf{E}^{\text{e}}, \alpha, D, T_{\text{temp}}) \end{aligned} \tag{3}$$

for the isotropic hardening and the damage, respectively. s denotes the specific entropy.

Please cite this article in press as: K. Isik et al., Modelling of the blanking process of high-carbon steel using Lemaitre damage model, C. R. Mecanique (2018), https://doi.org/10.1016/j.crme.2018.05.003