C. R. Mecanique 344 (2016) 296–318

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

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Computational simulation of manufacturing processes

Ductile damage prediction in sheet and bulk metal forming

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ARTICLE INFO

Article history:
Received 5 October 2015
Accepted 21 November 2015
Available online 2 March 2016

Keywords:
Non-associative plasticity
Anisotropic plasticity
Nonlinear hardening
Anisotropic damage
Numerical methods
Metal forming
Numerical simulation

ABSTRACT

This paper is dedicated to the presentation of an advanced 3D numerical methodology for virtual sheet and/or bulk metal forming simulation to predict the anisotropic ductile defects occurrence. First, the detailed formulation of thermodynamically-consistent fully coupled and fully anisotropic constitutive equations is given. The proposed constitutive equations account for the main material nonlinearities as the anisotropic plastic flow, the mixed isotropic and kinematic hardening and the anisotropic ductile damage under large inelastic strains. Second, the related numerical aspects required to solve the initial and boundary value problem (IBVP) are very briefly presented in the framework of the 3D finite element method. The global resolution schemes as well as the local integration schemes of the fully coupled constitutive equations are briefly discussed. Finally, some typical examples of sheet and bulk metal forming processes are numerically simulated using the proposed numerical methodology.

1. Introduction

The main objective of modern metal forming processes is to design robust and lightweight structural components which help reducing carbon dioxide emissions during both the manufacturing process as well the future use of the final product. Accordingly, the rising demands of customers concern the lightweight design in order to reduce significantly energy consumption and cost efficiency while increasing the structures' service life by enhancing their stability and deformation resistance under various thermomechanical loading paths. These objectives cannot be reached without the help of an 'efficient' and 'robust' numerical or virtual design methodology based on:

- 'advanced' constitutive equations to describe, as accurately as possible, the main thermomechanical fields and their various interactions (full coupling effects) during their evolution,
- 'advanced' numerical tools to predict robustly and accurately the evolution of the deformation processes and the possible defects occurrence during the manufacturing processes or during the use of the final component in any mechanical system.

In fact, when formed or machined by large elasto-inelastic strains under room or high temperature, metallic materials undergo a strong localization of inelastic flow which is often at the origin of the initiation, growth and coalescence of microcracks and/or microvoids usually called the ductile damage. Depending on the geometrical complexity of the forming

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http://dx.doi.org/10.1016/j.crme.2015.11.006

tools, which define the shape of applied loading path, this well-known mechanism of ductile fracture may cause the loss of the quality of the formed part by the formation of macroscopic cracks propagating inside this formed part. This ductile damage can be seen as a natural consequence of the large inelastic strain localization which itself is strongly dependent on the main thermomechanical phenomena such as the mixed isotropic and kinematic hardening, the heat flux, the various initial and induced anisotropies, the initial microstructure of the material and its change (texture) under the applied loading paths. Accordingly, the constitutive equations used to simulate and to optimize numerically these metal forming processes should account for these phenomena and their mutual interactions or strong coupling.

Many published works have been devoted to the optimization of bulk and sheet metal forming processes using various more or less simplified approaches. For example, in the forming of thick or thin metallic sheets, the goal is to enhance the capacity of the sheet to carry a large inelastic "homogeneous" strain without any strong localization, giving some through thickness necking prior to a macroscopic crack formation. In engineering practice, the material formability is usually assessed with strain-based forming limit diagrams (FLD) in the case of linear (or proportional) strain loading paths as pioneered by Mariciniak and coworkers [1,2]. These forming limit diagrams or curves are determined from the experimental measurement of the necking or local fracture onset under linear strain paths using the minor and major principal strain diagram. However, it has been shown [3–10] that these strain-based forming limit criteria are not efficient when the applied strain path is not linear (or is non-proportional). Unfortunately, in major forming processes, the strain paths supported by deforming material points during the deformation process have been shown to be neither linear nor monotonic. This is mainly due to the complexity of the geometry of the tools (dies, punches), which cause locally reversed strain path exhibiting non-negligible Bauschinger effects. This is clearly the case in sheet-forming processes, for which the FLD prediction underestimates the failure strain as observed in many works (see [11–16] among others). To avoid these drawbacks, some authors proposed to construct the FLD (or FLC) in the stress space instead of the strain space, leading to the so-called stress-based forming limit diagram, FLSD [3–10]. However, this approach has been shown to be not efficient for complex combined stress paths (mainly non-proportional loading paths exhibiting additional hardening), where material hardening is strongly dependent on the shape of the loading path [12,13,17]. On the other hand, when necking takes place somewhere in the sheet, the plane stress assumption, on which is based the FLSD, becomes highly questionable and the predicted local stress state is less accurate or simply wrong.

Another way, proposed in many works in order to enhance the predictivity of the forming limit curves, consists in completing the yield function, of von Mises or Hill types, by appropriate instability criteria based on the pioneering works by [18–20]. Most instability theories assume the existence of an initial imperfection with a given geometrical definition, leading to a high sensitivity to the size of such an assumed initial imperfection. On the other hand, the prediction of plastic strain and its value at the final fracture is highly dependent on the used constitutive equations and on whether or not they account for non-linear mixed isotropic and kinematic hardening as well as the ductile damage effect on plastic flow and hardening evolution. In order to avoid this problem, many authors proposed to replace the initial imperfection by using an appropriate ductile damage theory, which allows catching naturally the instability conditions due to the damage initiation without assuming the existence of any initial imperfection [21–24] among many others.

An alternative approach, proposed in the recent last two decades, to predict the localized neck prior to fracture in sheet or bulk metal forming, is the full coupling between the material's behavior and the ductile damage using either macroscopic monoscale or micro–macro multiscale modeling approaches as can be found in the recent books dedicated to the damage prediction in metal forming [25–27]. Two different kinds of damage theories are used in metal forming problems: Gurson's damage theories [28–37] (among others) and continuum damage mechanics (CDM) theories [26,27,38–74]. The equivalence between CDM and Gurson-type damage coupling has been investigated in [54], where the potentialities of the CDM approach compared to Gurson's approach have been discussed mainly concerning damage-induced anisotropy and its effect on the other fields (strong coupling). This kind of fully coupled approach accounts for the direct interactions (or strong coupling) between the inelastic flow, including different kinds of hardening, and the ductile damage initiation and growth. This full coupling allows the "natural" description of the strain localization modes inside the deformed part on the basis of the effect of the ductile damage evolution in the other mechanical fields under concern. Hence, it provides a simple and helpful way to predict where and when the inelastic flow localizes due to the earliest stage of ductile damage initiation without reference to any initial imperfection. The main advantages of this fully coupled approach are [26,27]:

- it can be used, without any limitation, with advanced constitutive equations accounting for initial and induced anisotropies described by various quadratic or non-quadratic yield functions and plastic potentials. Many physical phenomena related to large inelastic strain coupled with ductile isotropic or anisotropic damage can be taken into account;
- the effect of the loading path shape in the stress or strain space (non-proportionality) and in time (cyclic loading) is considered, including the reversibility of the load with or without compressive phase. This accounts for:
  - the Bauschinger effect (kinematic hardening),
  - the closure of microcracks and/or micro-voids (unilateral effect) under the compressive phase of the loading path and its effect on the recovery of some physical properties as the microcracks close;
- due to the localization modes giving rise to highly varying thickness, this approach will be used within full 3D or specific thick shell formulations in order to avoid the weakness related mainly to the plane stress assumption.