Damage mechanics approach for predicting material processing defects

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Abstract

Damage theory has been successfully introduced over the last two decades for predicting and avoiding the occurrence of defects in manufactured products. Advanced methods have been proposed to characterise the workability of a material and to estimate the resultant soundness of the manufactured products, obtained by different operations such as: deep drawing, forging, rolling, etc. The keynote lecture reviews the main damage models and significant applications in this field.

1 Introduction

The occurrence of defects in manufactured products and, more appropriately, defect avoidance by limitation of material deformation and processing have always represented the main focus of all sectors of the manufacturing industry. The range of fabrication and material working defectiveness encompass:

a) the occurrence of defects due to interactions between workpiece materials, tooling, friction and process geometry;
b) some forms of material structure which result from purely mechanical action;
c) elastic spring back and generated residual stresses;
d) the limits of performance imposed by the material properties themselves with respect to a given tooling.

The list of most common defects arising in the processing of metals and composite materials, published by Johnson and his associates [1] – [4], is impressive (more than two hundred defects are mentioned). The defects are
classified according both to the main working operations (rolling, forging, extrusion, drawing, bending, etc.) and to the nature of the material (metals, fibre-reinforced plastics, metal-matrix composites, coated materials).

The nature of defects is varied, but most of them are due to internal or surface fractures (central bursts or chevrons, alligating, fir tree, edge cracking, etc.) and/or to instability phenomena (wrinkling, necking, earing, folding, etc.). In addition, thermomechanical treatment, spring back behaviour and tooling geometry can favour the occurrence of many other body or surface defects.

Among the microstructural rearrangements induced by extensive plastic straining during the forming processes, nucleation and growth of voids and cracks are the most important. This phenomenon, called damage, leads to a progressive deterioration of the material in the sense that it diminishes its resisting capacity to subsequent loading. An advanced evolution of damage favours the appearance of plastic instabilities and ductile fractures, internal or external, by coalescence of the microcavities. [5] – [6].

Practical consequences of these straining effects are unsatisfactory limitations in working operations and/or unacceptable products. Apart from the determination of forming limits, another equally important interest in the damage analysis is determining the “soundness” of the material undergoing a forming operation. As noted, the absence of apparent cracks on the free-stress boundary of a product does not exclude an advanced state of damage within the material itself. In[7], it is noted that metallographic examinations indicate that sub-surface void formation occurs prior to the appearance of a surface crack during the same bulk forming operations. It was also noticed that, for less ductile materials, fracture occurs through the full section and is not confined to the bulge equator area of the cylindrical upset specimen.

Since the internal microstructure of the material is strongly affected by damage phenomena, the mechanical and physical properties are consequently also modified. The global (macroscopical) rheological behaviour of the material will therefore be dependent both on the “initial” state of damage and on its evolution during the deformation process. Conversely, every stage of damage evolution (nucleation, growth, coalescence) is controlled by stress and strain fields at both microscopic and macroscopic levels. Therefore, the coupling of damage effects with plastic deformation must be included in constitutive modelling.

2 Damage mechanics approach

Some of the main defects arising in metal working processes have already been singled out in the literature and tentative methods have been proposed to explain them by using slip-line field theory and upper- and lower-bound techniques of limit analysis (see for instance the books [8] – [13]). But as it known, the limit analysis of plasticity theory is one alternative to the absence of precise solutions. On the other hand, no prediction of the evolution of defects can be provided by such methods.

A significant advance was made in the 1980’s by introducing the mathematical modelling of damage into defects analysis.
The series of conferences devoted to predictive methods of material processing defects, initiated by the author in 1987, has drawn attention to this new approach (see the proceedings of these conferences [14] – [17]).

The inclusion of the degrading microstructure of the material during deformation into a continuum mechanics model requires the introduction of new field variables describing the damage state. This idea was originated by Kachanov [18] in 1958 for uniaxial creep behaviour and then developed by Rabotnov [19] in 1968 for three dimensional cases by introducing the concept of effective stress. Continuum damage mechanics was born, yet the name of this new branch of continuum mechanics would appear only ten years later [20].

Essentially, two classes of damage variables can be distinguished:
a) damage variables which take into account the distribution and morphology of the microvoids and their effects on the kinematic fields (a difficult task!). By using averaging techniques and simplified geometrical models for the void-containing material, such “kinematic” damage variables have been defined [21], [22]. Most of these models are surfacic models, designed to evaluate the net resisting area. These approaches lead to representing the damage variables by scalars for isotropic damage or by vectors and tensors of different orders (second or fourth order) for anisotropic damage (see review paper [23], [24]),
b) damage variables which describe the changes in mechanical and physical parameters or which can be identified with some of these parameters (elastic moduli, density, for instance). These damage variables represent partial “indicators” of the degraded state of the material. Damage variables, belonging to one or another class, can be considered internal variables in the sense of the thermodynamics of irreversible processes. Depending on the scale level of the damage analysis, the damage variables can be defined at the micro, meso or macro level. When the state fields present non-uniform spatial fluctuations at the microscale, a non-local continuum theory of damage has been proposed as an alternative theory [25] – [26].

The constitutive model can be developed within the framework of irreversible thermodynamics with internal variables in order to include damage effects such as:
i) gradual degradation of elastic properties,
ii) strain softening effects on the yielding behaviour of the material volume element,
iii) plastic dilatancy due to nucleation and growth of microvoids.

The general structure of the stress-strain relations can be based on two thermodynamic potentials: a free-energy potential determining the elastic damage response, and a dissipation potential to define the plastic flow and damage evolution equations.
2.1 Ductile damage models. Examples

a. The model originated by Kachanov [18], introduces the damage variable $D(x,n)$ at point $x$ and in the normal direction $n$ as a ratio of the damaged surface area $s_d$ to the total cross-sectional area of a surface of a representative volume element (r.v.e) about a normal direction $n$, $D(x,n) = \frac{s_d}{s}$.

It follows that $0 \leq D \leq 1$, where for the undamaged state $D = 0$, and for the rupture case $D = 1$. For anisotropic damage, $D$ does not depend on $n$ and becomes a scalar variable. For anisotropic damage, $D$ is represented by a tensorial variable as described in [27] for instance. A simplified approach for modelling anisotropic damage using two scalar variables associated with the loading direction has been proposed in [28].

The application of the Kachanov model to multiaxial loading is performed by means of the concept of effective stress $\tilde{\sigma}$ relative to the resisting area $s - s_d$ and defined by $\frac{\sigma}{1-D}$, where the Cauchy stress tensor is relative to $s$. For anisotropic damage, the concept of effective stress is generalised by means of an operator $M(D)$, i.e. $\tilde{\sigma} = M(D)\sigma$ [29] - [31].

The deduction of the stress-strain relations for a damaged material is obtained by using an equivalence principle. According to the strain equivalence principle [32], a strain constitutive equation for a damaged material is obtained by using the stress-strain relations for an undamaged material by replacing the stress by the effective stress $W_e(\sigma, D) = W_e(\tilde{\sigma}, D)$ [29], [33].

A simplified form of the stress-strain relations defining elasto-plastic damage model can be found in [34] - [35] and a revised theory including the contributions of the plastic flow in damage evolution in [33]. This model has been formulated and used for large deformations as well (see [36] for a synthesis). The evolution law for damage variable $D$ is obtained by assuming particular forms for the dissipation potential.

For instance, in [35], the evolution equation has been proposed:

$$\dot{D} = \frac{Y}{S} \dot{p} H(p - p_D),$$

where $Y = \frac{\sigma_{eq}^2 R_v}{2E(1-D)^2}$, $R_v = \frac{2}{3} (1 + \nu) + 3(1-2\nu) \left( \frac{\sigma_H}{\sigma_{eq}} \right)^2$. (1)
\( \sigma_{eq} \) is the von Mises equivalent stress, \( \sigma_H \) the hydrostatic stress, \( p \) the accumulated plastic strain, \( p_D \) the threshold of \( p \), \( H \) the Heaviside function, \( E \) the elastic modulus, \( v \) Poisson's ratio and \( S \) a material constant.

Various measurements of damage have been proposed, but the most widely used is based on the variation of the elasticity modulus [35]

b. A second type of isotropic damage model, used more extensively in defect analysis, introduces a volumic variable to characterise the damage state of the material, namely the void-volume fraction, defined by \( f(x) = v_a - v_m/v_a \), where \( v_a \) and \( v_m \) are the elementary apparent volume of the material and the corresponding elementary volume of the matrix respectively.

To define the stress-strain relation for a damaged material, approximate expressions for the macroscopic potentials have been derived using the micro-mechanical analysis of the representative volume element for various types of specific constitutive behaviour of the matrix. For instance, rigid perfectly plastic behaviour was considered by Gurson [37] in 1977 in his deduction of the well-known field criterion, which was slightly modified by Tvergaard [38] in 1981 to account for void interaction effects:

\[
\psi = \frac{\sigma_{eq}^2}{\sigma_M} + 2f_1q_1 \cosh \left( \frac{q_3 - \frac{\text{tr} \sigma}{2 \sigma_M}}{2} \right) - 1 - q_3f^3 \tag{2}
\]

where \( \sigma_M \) is the flow stress of the matrix. Gurson's model is obtained for \( q_1 = q_3 = 1 \) or \( q_3 = 3 \), corresponding to the cylindrical or spherical void model, respectively.

Other variants of the ductile damage model based on porosity have been proposed. In [39], the damage state is characterised by the density \( \varphi \) of the material and in [40] by the volume change \( \text{det} F^d \), associated with the deformation gradient component \( F^d \), which accounts for the damage effects \( F = F^eF^dF^p \), where \( F \) is the total deformation gradient, \( F^e \) is associated with elasticity and \( F^p \) with plasticity effects).

The evolution equation for the void volume fraction can be assumed in the following form:

\[
\dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \tag{3}
\]

for which, in general, heuristic laws have been proposed for \( \dot{f}_{\text{nucleation}} \) and \( \dot{f}_{\text{growth}} \) respectively.

The void growth equation generally results from the conservation of mass:

\[
\dot{f}_{\text{growth}} = (1 - f) \text{tr} D^p \tag{4}
\]

where \( D^p \) is the plastic component of the deformation tensor. The thermal aspects in modelling porous media behaviour have been reviewed in [41].
3 Applications to defects analysis

The inclusion of a damage model into the description of a plastic deformation process has provided a new approach to both formability limits and the characterisation of forming-induced effects, in particular the deterioration of the material, i.e. damage state.

Some significant applications concerning the iso-damage charts, forming limit curves and fracture initiation in metal-forming processes can be cited:

3.1 Iso-damage charts

The evaluation of damage, defined by surfacic or volumic variables, has been estimated for the following forming operations: extrusion [42] – [45], upsetting [46] – [47] H-shaped cross-sectional forging [48], pipe-bulging [49], strip drawing [50], deep-drawing [51], as well as for deformation tests such as collar-testing [52], torsion-traction [53], or extension of a notched rod [54] – [55].

Corroborating the damage evolution with a plastic instability analysis of cold upsetting in [46], sizable deterioration effects have been detected inside the product and on its free-stress boundary. It was shown that the formability analysis by means of just the “apparent” cracking observations is not always satisfactory.

3.2 Forming limit curves

From a practical point of view, two types of forming limit curves (f.l.c) are equally interesting: fracture f.l.c. and necking f.l.c. To be determined, appropriate ductile fracture criteria must be added to the governing equations. Many such criteria have been proposed. We can state that the criteria taking into account the damaged state of the material can lead to reliable predictions of the occurrence of defects. In [56] – [58], the fracture f.l.c. are determined by using the Kachanov damage model and the local fracture condition defined by a critical value of damage variable $D$.

The determination of the striction f.l.c. including the damage state of the material, has been considered in several studies, but only including an initial state of damage, which is non-evolutionary, either as geometrical imperfections or structural imperfections [59].

More suitable predictions of the striction f.l.c. with respect to experimental data have been obtained by using a coupled strain-damage model and localised striction criteria [60], [61].

In [62] the forming limit curves are deduced for Nakazima’s test and in [63] for Marciniak’s test.

3.3 Fracture initiation

The prediction of ductile fracture occurring in forming operations, by using a damage mechanics approach, has been proposed for central bursts during...
extrusion [44], or during drawing [64] – [66]. Failures in collar testing operation [52] or in sheet metals blanking [67] have also been predicted. To predict crack initiation a critical value of a damage variable is used either $D_c$ or $f_c$ which depends upon the material and the loading condition. As remarked in [68], the damage defined as porosity is very localised at fracture. Its value depends on the stress triaxiality evolution during deformation until fracture. It reaches 15% for upsetting but in tensile specimens, it stays around just a few percent.

4 Concluding remarks

The prediction of material processing defects using a damage mechanics approach has already produced important results and represents a real challenge in the near future. Modelling the anisotropy induced by industrial processes, by means of tractable damage models, improvements in evolution laws for damage by microscopic analysis, definition of realistic fracture criteria, experimental characterisation of models, are a few of the future research topics in this field. In order to use fully coupled damage models in finite element simulations, some algorithmic refinements have already been carried out (see, for instance, [69]). A major problem remaining to be solved is the mesh dependency of the results due to the localisation of plastic flow.

References


