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Influence of damage on the plastic instability of sheet metals under complex strain paths

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During the sheet metal forming operation, internal damage occurs as a result of nucleation growth and coalescence of cavities around particles. This phenomenon limits the strains which can be achieved before the appearence of localized necking. In this paper, damage is represented by initially equi-axed cavities and a void growth model is extended and linearized for complex strain paths. For a given void distribution, a statistical study pointed out the existence of weak sections in the material leading to localized plastic flow. The influence of the physical parameters of voids on the forming limit diagrams is shown.

1. Introduction

Energy saving is an important problem in the automobile industry that requires the use of steels of increasing strength. Such high characteristics are generally obtained by additions of alloying elements or by treatments leading to dual-phase materials. In both cases the effect is usually to increase the number of hard particles in the ductile matrix. In the case of sheet metal forming involving large plastic strains, cavities can nucleate at these hard particles with two main mechanisms: decohesion between the matrix and particles (equi-axed) or failure of the particles (elongated). This internal damage has a great influence on the plastic behaviour of the materials. In particular, it leads to premature necking and can drastically decrease the fracture strain.

The aim of this work is to analyse the influence of this damage on the forming limit of materials subjected to complex strain paths. In this analysis the internal damage is modelled by initially equi-axed cavities. A typical example of this type of damage is shown in Fig. 1.

In order to determine the forming limit, a plastic instability calculation is carried out from a two-zone material [1, 2] (Fig. 2). The constitutive behaviour of the material is assumed to be isotropic, to follow the J_2 flow theory of plasticity and to present isotropic strain-hardening described by:

$$\sigma = K(\bar{\epsilon} + \bar{\epsilon}_0)^n \dot{\bar{\epsilon}}^m,$$

where K, $\bar{\epsilon}_0$, n, m are constants and σ, $\bar{\epsilon}$, $\dot{\bar{\epsilon}}$ are, respectively, the equivalent Mises-stress, effective strain and strain-rate.

2. Theoretical procedure

A uniform plane stress state is applied to the homogeneous region (a) of the model material. Both linear and complex strain paths consisting of two linear branches are considered [3, 4]. The limit strains are achieved when the plastic flow localizes only in the neck region. The computations strongly depend on the neck orientation and the forming limit is obtained for the orientation minimizing the limit strains.

The defect in the material can be interpreted in terms of internal damage, and thus the reduction in section area is due to the presence of voids. The problem is, therefore, to find the equivalent section defect representative of a given damage distribution. This is achieved by a statistical analysis: the first step is to determine the probability of the existence of a punctual defect due

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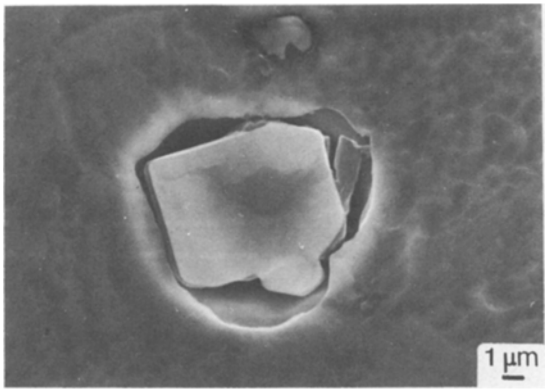

Figure 1 Damage by decohesion between the matrix and an alumina particle in a dual-phase steel sheet.

to the alignment of cavities in the sheet's thickness direction [5]. In the case of cavities having the same size and being randomly distributed, the probability of finding an alignment of x cavities is given by:

$$p(x) = \binom{\nu}{x}(C_v)^x \cdot (1 - C_v)^{\nu - x},$$

where C_v is the volume fraction of cavities and ν the ratio of the thickness of the sheet to the thickness dimension of the cavity: $\nu = t/D_3$. The present analysis can be extended for the case of two classes in size of cavities.

Necking will develop in an approximately linear band that will join the maximum number of punctual defects. An image of this band of damage can be obtained by representing in the plane of the sheet the sites with or without a punctual damage defect. In Fig. 3, a typical image of defects is drawn. It is worthy to note that this band presents a high concentration of defects. The mean linear defect can be calculated by the mean of the different punctual defects affected by their own probability and taking into account the fact that the continuity of the band can be interrupted by small defect-free regions. The resultant mean defect depends only on the volume fraction of voids and the characteristic ν ratio.

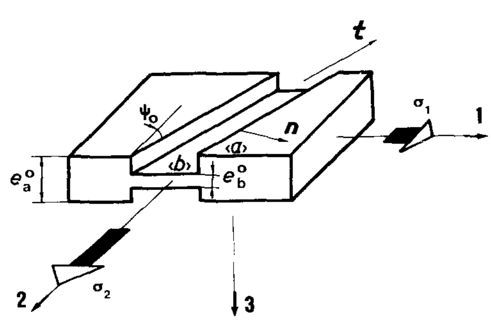

Figure 2 Model of localized necking in the Marciniak–Kuczynski analysis.

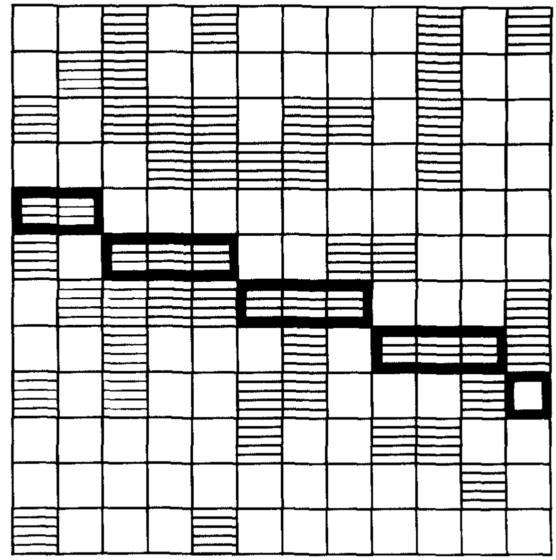

Figure 3 Location of the punctual defects in the plane of the sheet (shaded area). A quasi-linear band joining a maximum number of punctual defects is represented.

The simulation has been performed for a given volume fraction of voids and ν ratio and during straining the evolution of these parameters has to be considered. A void growth model, therefore, has to be used: the approach of Rice and Tracey [6] has been selected as a basis and modified for the loading conditions considered [7]:

$$\dot{R}_i/R_i = C\dot{\epsilon}_i + S\dot{\bar{\epsilon}}$$

where $C\dot{\epsilon}_i$ is a deviatoric term associated with a change in shape at constant volume and $S\dot{\bar{\epsilon}}$ is a spherical term associated with a homothetic change in volume. The evolution of the coefficient S as a function of the ratio of the thickness strain increment to the equivalent strain increment is presented in Fig. 4 for the range of strain paths considered (from uniaxial tension to equi-biaxial stretching). This evolution can be approximated by a linear equation:

$$S = -K\mathrm{d}\epsilon_3/\mathrm{d}\bar{\epsilon},$$

where K is a constant ($K = 0.64$). The void growth model can be rewritten as:

$$\mathrm{d}R_i/R_i = C\mathrm{d}\epsilon_i - K\mathrm{d}\epsilon_3.$$

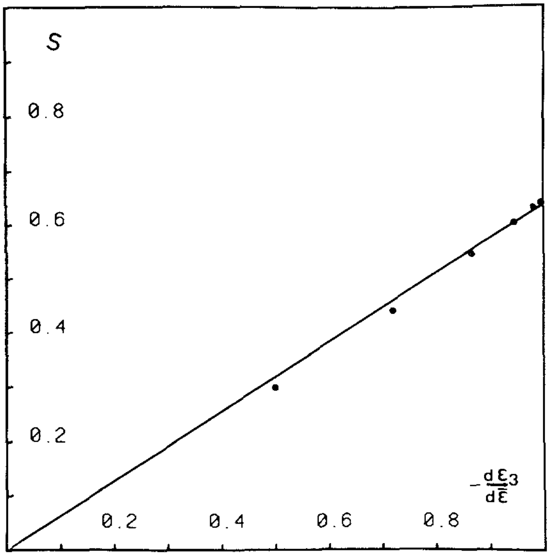

Figure 4 Relationship between the spherical term S of Rice and Tracey's model and the ratio of the thickness strain increment to the effective strain increment $d\epsilon_3/d\bar{\epsilon}$. A good linear approximation can be drawn.

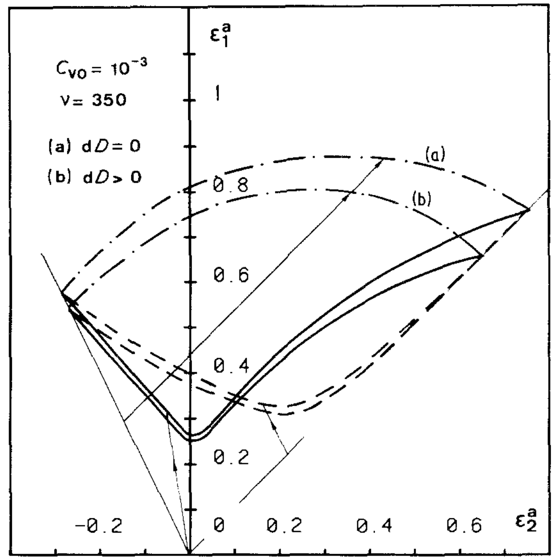

Figure 5 Effect of damage evolution on the FLDs. (a) Curves computed for an initial defect without void growth. (b) Curves computed for the same initial defect and taking into account the growth of voids.

The volume fraction of voids depending on the spherical part is found to be only a function of the thickness strain, whatever the strain path is:

$$C_v = C_{v0} \exp(-3K \cdot \epsilon_3).$$

This result is consistent with experimental observations [8]. The extension of this void growth model to hardening materials with a low stress triaxiality is assumed to be valid [9].

3. Results and conclusions

In the present investigation the plastic instability calculations are performed considering all the cavities initially present in the material [10, 11]. Nucleation can be introduced through a nucleation function [12]. Furthermore, it is assumed that no interaction occurs between voids.

The process of instability described by the model is two-fold:

1. the inital defect derived from the initial damage will increase by inhomogeneous plasticity;
2. the internal damage will grow, leading to an additive increase of the defect.

The effect of void growth can be emphasized by performing two calculations starting with initial damage and allowing (or not allowing) damage evolution to occur by void growth. The results presented in Fig. 5 show a decrease in the formability especially in equi-biaxial stretching for direct linear strain paths. The forming-limit diagram (FLD) has also been calculated for complex strain paths consisting of two linear branches:

1. uniaxial tension followed by equi-biaxial stretching (TE);
2. equi-biaxial stretching followed by uniaxial tension (ET).

The influence of damage growth is sensitive on the TE FLD where the decrease of formability can reach 20%. The shapes of the FLDs in Fig. 5 can be explained by the behaviour of the damage growth: little growth in uniaxial tension and large evolution in equi-biaxial stretching.

The effect of the initial volume fraction of cavities can be predicted for a given radius of initially spherical cavities in a material of a given thickness (Fig. 6). In other words, the only floating parameter is the number of cavities per unit volume. The calculation has been performed for observable values of the initial damage in cold-rolled materials ($C_{v0} = 5 \times 10^{-4}$, 10^{-3}) and for a reasonable upper bound value (5×10^{-3}). As mentioned previously, the influence of damage is the more important in equi-biaxial stretching and on the TE FLD. Moreover, it can be seen that the internal damage is a very sensitive parameter and therefore its control is of prime importance.

In the calculation, the parameter ν defined as the ratio of initial thickness of the sheet to the

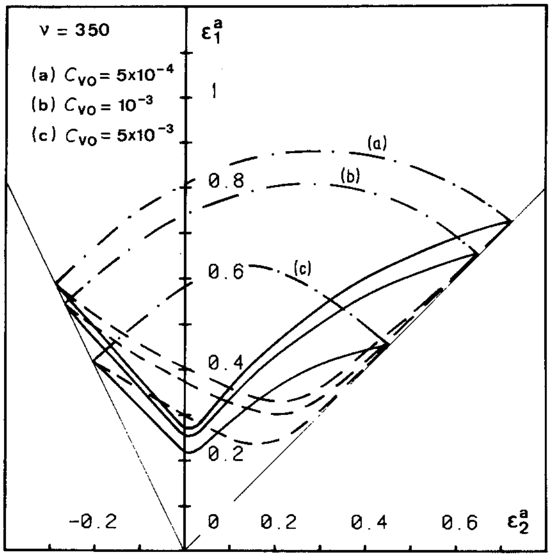

Figure 6 Effect of the initial concentration of voids (C_{vo}) on the FLDs.

initial void radius, has been introduced into the statistical analysis. For a given initial damage, the effect of ν is presented in Fig. 7. The influence of this parameter is quite significant: the greater is ν, the higher is the FLD. This result can have two interpretations:

1. for a given initial thickness, ν is inversely proportional to the initial void radius. This means that it is less critical to have a large number of

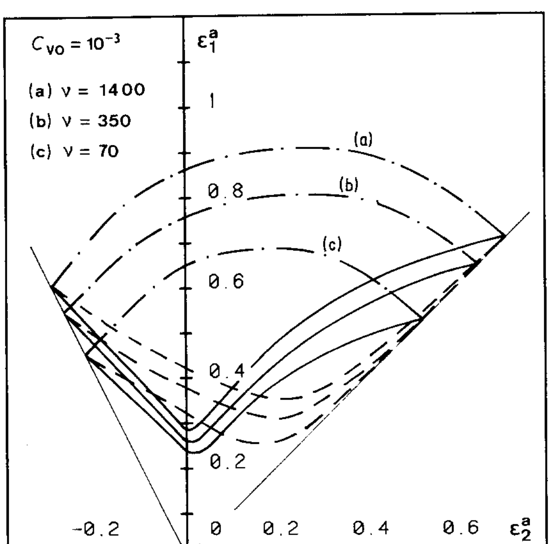

Figure 7 Influence of the parameter ν (ratio of the thickness of the sheet to the thickness dimension of the cavities) on the level of the FLDs for a given volume fraction of voids.

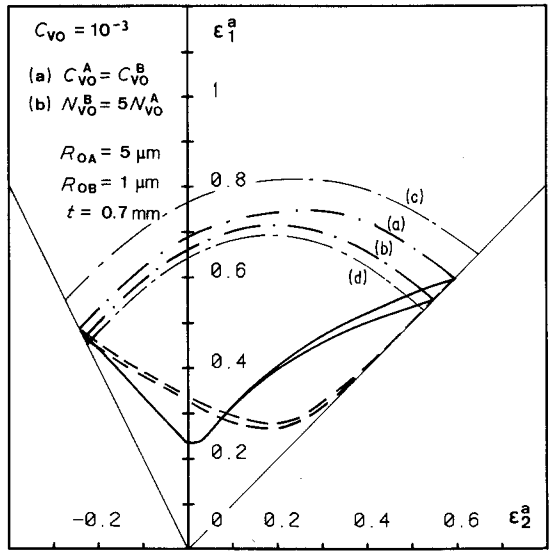

Figure 8 Effect of two classes (in size) of cavities for a given volume fraction of voids. (a) Curves computed for an equal volume fraction of voids in the two classes. (b) Curves computed for a ratio of the number per unit volume of small cavities to large cavities equal to 5. (c), (d) The bounds for one class of voids.

small cavities than a small number of large cavities for a given volume fraction of voids;

2. for a given initial size of the cavities, ν is proportional to the thickness of the sheet. This means that the level of the FLD increases with increasing sheet thickness. This result is in agreement with numerous experimental observations [13–15].

Most often in industrial materials the size of the cavities is not uniform. A first approach is to consider two classes of cavities of different size (A and B). A calculation has been performed with the following parameters (Fig. 8): large cavities (class A), $R_{0A} = 5\,\mu$m; small cavities (class B), $R_{0B} = 1\,\mu$m, where R_0 is the initial radius of the cavities. The relative volume fraction of each class can vary keeping a constant overall volume fraction of cavities. Two bounds can be obtained assuming the presence of only one class (cases c and d TE FLD in Fig. 8). One intermediate approach is to impose the same volume fraction for each class (case a) or, as usually observed, to have a larger number of small cavities ($N^B = 5N^A$, case b). From these results it can be seen that the major effect of damage on the FLD (specially TE) is due to the large cavities. In many cases and in a first approach, the effect of the small cavities can be neglected.

This work is a step towards the prediction of the forming limits of complex parts submitted to non-linear strain paths. Particularly, damage growth evolution is given for complex strain paths along which plastic instability calculations can be performed.

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