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Internal micronecking as a factor of the process of ductile fracture of metals(*)

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A THEORETICAL and experimental study of interaction betwen parallel cracks leading to internal micronecking is presented in an attempt to obtain a deeper insight into the process of ductile fracture of metals. Theoretical analysis of the internal micronecking is based on the slip-line technique. Experiments on specimens of ductile metal with prepared cracks substantiate the analysis.

Przedstawiono teoretyczne i doświadczalne studium oddziaływania między równoległymi szczelinami w celu głębszego poznania procesu ciągliwego pękania metali. Teoretyczną analizę tworzenia się mikroszyjek przeprowadzono przy użyciu teorii linii poślizgu. Doświadczenia przeprowadzone na próbkach z ciągliwego metalu, w którym wykonano odpowiednie nacięcia, potwierdzają analizę teoretyczną.

Представлены теоретические и экспериментальные исследования взаимодействия между параллельными трещинами с целью более глубокого познания процесса вязкого разрушения металлов. Теоретический анализ образования микрошеек проведен при использовании теории линий скольжения. Эксперименты проведены на образцах из вязкого металла, в которых сделаны соответствующие нарезки, подтверждают теоретический анализ.

1. Introduction

COALESCENCE of voids as a factor responsible for the ductile fracture of metals has been analysed by MCCLINTOCK [1]. NAGPAL *at al.* [2] used the plane strain theory of a rigid-plastic material with cylindrical holes to develop criteria for the localization of plastic flow which leads to ductile fracture. The growth of spherical holes has been studied by RICE and TRACEY [3]. The experimental evidence for ductile fracture by the growth of holes has been known for a number of years (see for example [1] and [4]).

Also the mechanism of internal necking has been discussed in several works in connection with ductile fracture. In order to demonstrate the influence of structure on the ductility of metals, ROGERS [5] compared the tensile ductility of two theoretical models. One is a cylindrical rod of a perfectly plastic material and the other is a cable of equal external diameter consisting of a bundle of cylindrical strands. Each of the strands behaves in the same manner as a single rod, necking down to a point. A similar mechanism of ductile fracture of tensile specimens was discussed in [4] and [6].

The real physical significance of the mechanism of internal necking has been confirmed by Rhines who simulated it in Plasticene, as reported in [1]. His experiments indicate

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that the necking of ligaments between holes or cracks may be studied on the basis of the theory of plasticity. Such an approach was used in [2] for the analysis of localization of plastic flow in a plane strain model with regular arrays of holes of various shapes.

An experimental study of the progressing fracture in the presence of holes was presented in [7].

In the present note a more general model of progressing ductile fracture by internal necking will be discussed.

2. Strain concentration in the presence of cracks

At the beginning let us consider the necking process of a plane strain rigid-plastic bar. The slip-line solution to this problem is shown in Fig. 1B. The initial system of slip-

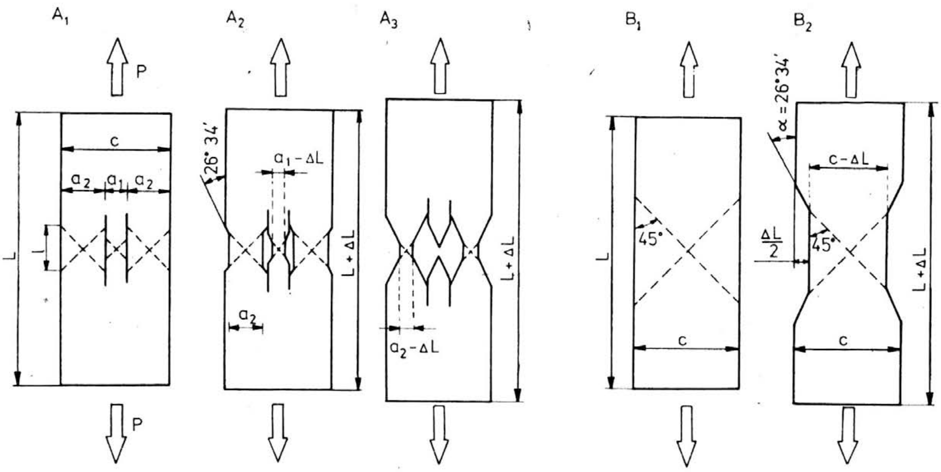

FIG. 1.

lines is presented in Fig. $1B_1$ and an advanced stage of deformation in shown in Fig. $1B_2$. From the condition of incompressibility we have the angle of inclination of the deformed boundary

$$\alpha = \operatorname{Arc}\tan\frac{1}{2} = 26^\circ\ 34'.$$

In the narrowest section of the neck the width is equal to $(c-\Delta L)$, where ΔL is the total elongation. Thus the conventional lateral strain may be written as

$$\varepsilon_c = -\Delta L/c. \tag{2.1}$$

Let us consider now an idealized plane strain model of the material with defects in the form of two slit cracks parallel to the direction of the uniaxial tensile stress (Fig. 1A). It is evident that if the elastic-plastic material is assumed there is no stress concentration in the elastic stage of the loading history. However, during the plastic stage of deformation there appears strong strain concentration due to the local necking of the ligaments between the cracks. In order to estimate the amount of this strain concentration we will assume that the model is made of a rigid-perfectly plastic material. Each of the ligaments necks down according to the deformation mode shown in Fig. 1B. Initial configuration of slip-lines is shown in Fig. $1A_1$. Plastic yielding begins when the pulling force P per unit thickness reaches the value $P^* = c\sigma_{pl}$, where σ_{pl} is the yield locus of the material. Fig. $1A_2$ illustrates how the strips separated by the slits begin to neck. In Fig. $1A_3$ the central strip is separated due to the necking down to a point, while the outer strips of larger width necked down only to certain degree without separation.

Let us consider the stage of deformation presented in Fig. $1A_2$. If the total elongation of the model is equal to ΔL, the lateral shortening of all three strips separated by the two slits will be equal to $-\Delta L$ which follows from the slip-line solution. Thus the conventiona lateral strain in central ligament is

$$\varepsilon_{a_1} = -\Delta L/a_1$$

and in the two outer strips it is equal to

$$\varepsilon_{a_2} = -\Delta L/a_2.$$

Comparing both values, we obtain the internal strain concentration factor

$$f = \varepsilon_{a_1}/\varepsilon_{a_2} = a_2/a_1, \tag{2.2}$$

which is valid for the intermediate stage of deformation when the central strip is not separated in two parts. Comparing the lateral strain in the narrower strip of the model with that in the block without cracks (Fig. $1B_2$), we obtain for the intermediate stage of deformation another definition of the strain concentration factor

$$f^* = \varepsilon_{a_1}/\varepsilon_c = c/a_1 \tag{2.3}$$

related to the width of the body. Such a strain concentration factor may reach in real situations very great values.

Since the analysis presented above is based upon the assumption of the idealized rigid-plastic model of the material with no strain hardening, simple experiments were performed in order to check whether the internal damage due to local micronecking may occur in real metals.

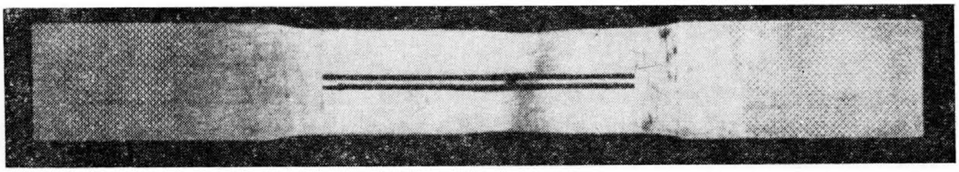

FIG. 2.

Figure 2 shows the specimen of an AlMg2 aluminium alloy deformed plastically by uniaxial tension. Two slits were prepared in the specimen according to the scheme presented in Fig. $1A_1$. It is clearly visible that the necking process is only slightly advanced in the two wide strips while the narrow central strip has been ruptured. This simple experiment shows that the theoretical analysis based on the slip-line technique presented above has a real practical significance. Thus the mechanism of local internal micronecking should be considered as one of the possible factors responsible for the process of fracture in metals.

3. Internal local micronecking as a measure of damage parameter

Let us analyse the history of deformation in a plane strain model with two parallel slit cracks analogous to that shown in Fig. 1 and subjected to repeated tension-compression loadings with the symmetrical strain amplitude. In Fig. 3 are presented seven stages of deformation during the first two cycles of loading with the strain amplitude $\pm\varepsilon^* = \dfrac{\Delta l^*}{c_0}$. Since in our model the plastic deformation is strongly localized, a conventional measure of strain $\varepsilon = \Delta l/c_0$ is assumed, where Δl is the total elongation of the model and c_0 stands for the initial width of the model.

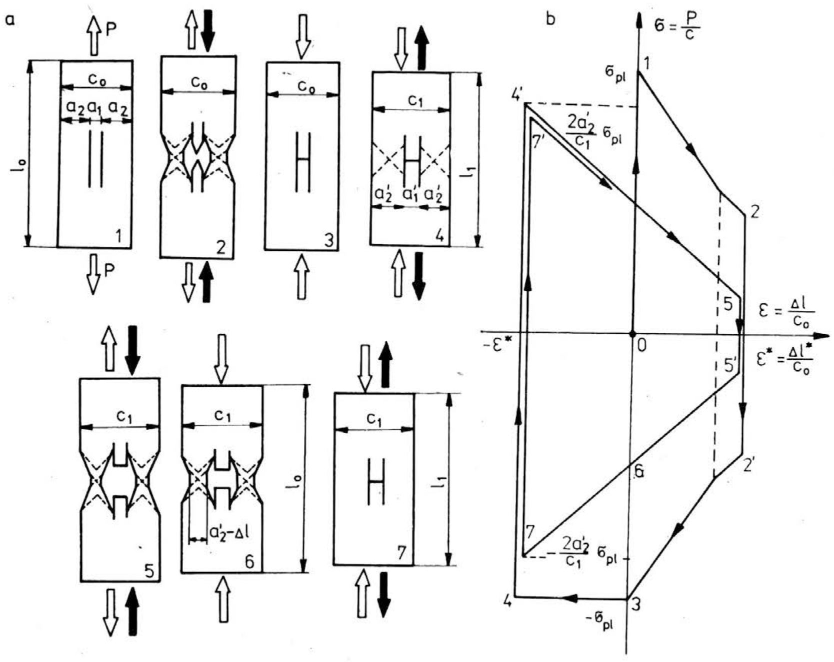

Fig. 3.

As in the previous analysis, we assume that the material is rigid-plastic with no strain-hardening. Consecutive stages from 1 to 7 show how the internal structure of the model changes during the first cycle of loading. Stage 1 shows the initial configuration. Plastic yielding begins when the pulling force per unit thickness reaches the value $P^* = c_0\sigma_{pl}$. Stage 2 is analogous to the final stage shown in Fig. 1 and the total length of the model is $l_0+\Delta l^*$. Between the stages 2 and 3, the model is compressed and the two separated parts of the central strip are flattened. This process leads to the configuration shown a the stage 3 with an additional horizontal crack between the two initial vertical cracks and the total length restored to the initial value l_0. Between the stages 3 and 4 the model is compressed up to the conventional strain equal to $\varepsilon^* = -\Delta l^*/c_0$ by the constant stress equal to the yield locus of the material σ_{pl}. Initial length l_0 is reduced to $l_1 = l_0 - \Delta l^*$ and spacings a_1 and a_2 increased to $a_1' = \dfrac{l_0}{l_0-\Delta l^*} a_1$ and $a_2' = \dfrac{l_0}{l_0-\Delta l^*} a_2$, respectively. Also the total width increases from c_0 to $c_1 = \dfrac{l_0}{l_0-\Delta l^*} c_0$. Thus the total force at the end of this stage of deformation is equal to $P = -\sigma_{pl} c_1$. When, subsequently, the tensile stress is applied, the two outer strips of the width a_2' begin to neck. This is illustrated in Fig. 3a by the stage 5 showing the situation for the conventional strain equal to $+\varepsilon^*$. For the following compression the length of the model is reduced again to l_1 (stage 7). The intermediate stage of deformation corresponding to the initial length l_0 is shown as the stage 6. Note that the configuration shown as the stage 7 is identical with that shown as the stage 4. Figure 3b shows how the stress-strain loop changes after the first cycle of loading.

The change of the internal structure after the first cycle of loading may be interpreted as a damage parameter. In our model the separated portion of the cross-sectional area of the width a_1' may be used as a measure of damage. Referring to Fig. 3a, the damage parameter may be defined as

$$\omega = a_1/c_0 = a_1'/c_1. \tag{3.1}$$

Note that this value of the damage parameter is valid also in the case when the deformation process is finished at the stage 3.

Let us assume that the deformation process is finished at the moment which in Fig. 3a is shown as the stage 6. Thus the final length of the specimen is equal after the deformation process to the initial length l_0, while its width has been increased to the new value c_1. It is seen that a cavity of complex shape is formed inside the model and the damage parameter defined as the relative reduction of the cross-sectional area may be written as

$$\omega = \frac{a_1' + 2\Delta l^*}{c_1}. \tag{3.2}$$

This simple analysis shows how the material may be weakened by the deforming processes if it initially contains imperfections in the form of microcracks.

Considering a model with a number of parallel slits in one cross-section, we may analyse the evolution of the damage parameter defined above. Let the ligaments between slits have various width a_i and let the number of ligaments of the same width a_i be n_i. Now, if the total equivalent strain $\varepsilon = \Delta l/c_0$ is within the range $(a_k/c_0) < \varepsilon < (a_{k+1}/c_0)$, the damage parameter ω is

$$\omega = \frac{1}{c}\left(\sum_{1}^{k} a_i n_i + \Delta l \sum_{k+1}^{m} n_i\right), \tag{3.3}$$

where c is the total initial width of the model (compare Fig. 1). The damage parameter ω reaches the value $\omega = 1$ (total separation) for the strain level $\varepsilon = \Delta l/c_0 = a_{max}/c_0$. Note that the first term in brackets is connected with the separation of the narrow strips and the second term corresponds to the reduction of the width of the wider strips due to necking.

Note that a part of the relative reduction of the cross-sectional area represented by the second term in Eq. (3.3) may be removed by the consecutive compression as shown in Fig. 3. The first term represents the irreversible part of the damage parameter.

4. Experimental study of the evolution of ductile fracture

The preliminary experimental result shown in Fig. 2 substantiates the concept of internal micronecking as a factor of the process of ductile fracture. Two following experiments presented below may be treated as a more complete study of the mechanical modelling of the micronecking process.

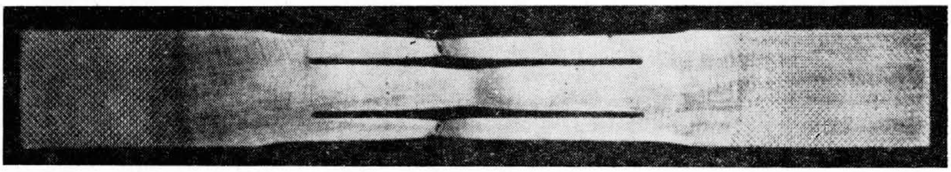

FIG. 4.

Figure 4 presents a plastically deformed specimen of an AlMg2 aluminium alloy (Polish symbol of the alloy PA2) with two narrow slits of 1 mm width prepared in the vicinity of the edges. The specimen was pulled in tension up to a fracture of narrow strips between the slits and external edges. It is clearly seen that both narrow strips have been ruptured while in the wider central strip the plastic deformation at the neck is only slightly advanced.

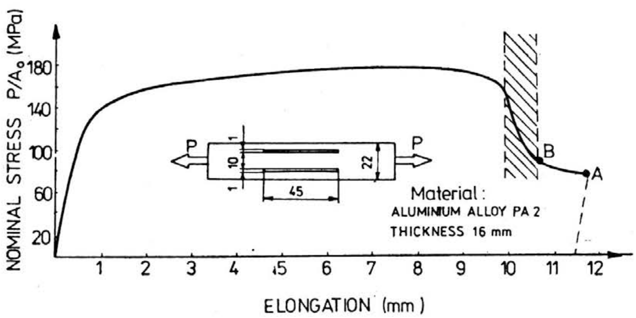

FIG. 5.

Figure 5 shows the nominal stress-elongation diagram. The tension test was stopped at the point A, which corresponds to the state of elongation shown in Fig. 4. The sudden drop of the pulling stress in the shaded area corresponds to the formation of the neck in the narrow outer strips. The total separation of these strips takes place approximately at the point B, whose exact position can hardly be defined. The further decrease of the nominal stress is connected with the evolution of the neck in the central strip.

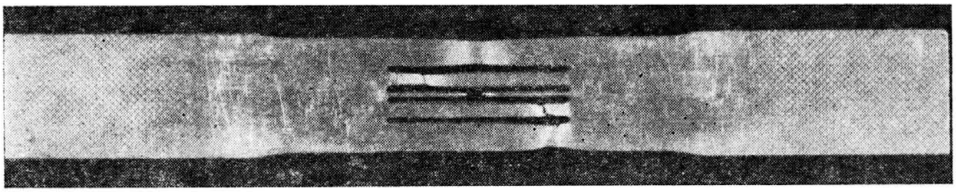

FIG. 6.

Figure 6 shows a plastically deformed specimen of the same alloy with four prepared narrow slits. The dimensions of the strips between these slits are shown in the inset in Fig. 7. The thickness of the specimen was 15 mm. Thus the conditions of plastic deformation were close to those of plane strain. In the final sector of the force-elongation curve, there appear sharp steps corresponding to the formation of necks in the consecutive strips

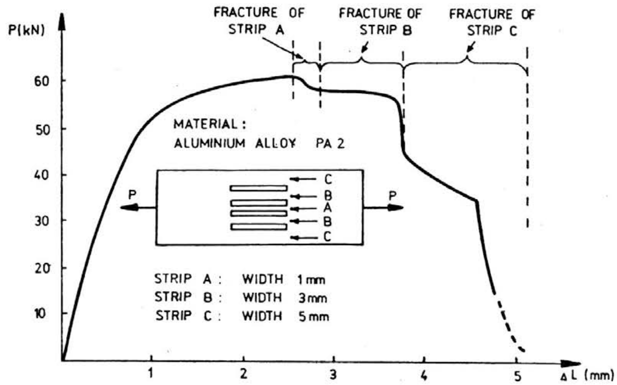

FIG. 7.

between the slits. After the fracture of the central narrow strip *A*, the specimen still displays quite a large carrying capacity and ability to deform plastically. The second step corresponds to the fracture of strips *B*.

5. Conclusions

The theoretical and experimental analysis presented above indicates that the process of internal micronecking connected with very high strain concentrations should be considered as an important factor in the study of complex phenomena of the ductile fracture of metals. The mechanism of internal micronecking may play an important role in the process of decohesion of ductile metals.

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