THE INFLUENCE OF STRESS STATE AND STRESS HISTORY ON CRACK OCCURRENCE

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ABSTRACT

The fracture occurrence in metal forming operations is one of the main limiting factors in the application of this technology. In the performing of deformation processes it is essential to create such a conditions which would prevent the fracture occurrence. One of the main influential factors on the cracks in metal forming processes is the stress and strain distribution within the deformation zone. This paper describes the free upsetting process from the formability point of view. Cylinder has been deformed incrementally until the first crack occurred and the stress and strain history has been evaluated at the most critical location for every increment. The procedure shown in this paper enables the creation of more points of forming limit curve for bulk metal deformation processes.

KEY WORDS

Ductile fracture, stress state, stress history, forming limit curve.

1. INTRODUCTION

One of the limiting factors in metal forming operations is the occurrence of ductile fracture which can take place on the specimen surface or inside the specimen volume (internal cracks).Fracture is a phenomenon dependent on the microstructure of the material in combination with the stress and strain state. For a given material different strains can be imposed in different working systems before cracking. The state of stress with predominant tensile stress components leads to early initiation of fracture whereas the compressive stress components allow for higher degree of deformation without cracks. The occurrence of first crack means the exhaustion of the formability potential of material e.g. the end of deformation process.

One of the very important task within the formability analysis is to predict the first crack e.g. to identify the conditions which lead to material cracking. The knowledge of the formability limit for certain material is essential not only for the optimum design of all process parameters but also for the maximum utilization of the material.

In order to predict fracturing in metal forming operations it is necessary to adopt the fracture criterion and to determine the stress-strain state for the given process. Formability characteristic of the analysed material must also be known.

The present paper deals with the problem of material formability limit (first cracks occurrence) in bulk metal forming operations such as free upsetting. The influence of stress-strain distribution on the formability potential and on the crack occurrence is analysed.

2. FRACTURE CRITERIA IN METAL FORMING

Fracture criteria in metal forming defines the conditions which must be fulfilled for the first crack occurrence.

A number of criteria have been developed for the fracture of ductile materials, some of those will be mentioned here.

Cockroft and Latham /1/ proposed one phenomenological criterion in the form:

$$\int_0^{\varepsilon_f} \sigma_1 d\bar{\varepsilon} = C \qquad (1)$$

where σ_1 - the highest tensile stress and C - the material constant.

Similar criterion was developed by Oyan /2/:

$$\int_0^{\varepsilon_f} \left[a_0 + \frac{m}{\bar{\sigma}} \right] d\bar{\varepsilon} = C \qquad (2)$$

where a_0 and C are material constants and $\bar{\sigma}$ is mean stress.

Freudenthal /3/ proposed the criterion in the following form:

$$\int_0^{\varepsilon_f} \bar{\sigma} d\bar{\varepsilon} = C_1 \qquad (3)$$

where C_1 is material dependent value, $\bar{\sigma}$ generalized stress , $\bar{\varepsilon}$ generalized plastic strain, ε_f strain at fracture.

The criterion suggested by Brozzo /4/ is given as:

$$\int_0^{\varepsilon_f} \frac{2\sigma_1}{3(\sigma_1 - \sigma_H)} d\varepsilon = W \qquad (4)$$

where W is the material constant (critical value for fracture), σ_H - hydrostatic stress.

The forming limit criterion for bulk metalworking processes, based on the magnitude of the hydrostatic component and the effective stress has been developed by Vujovic and Shabaik /5/. The authors emphasize the importance of the spherical (hydrostatic) stress component on fracture. They proposed the use of a parameter defined as follows:

$$\beta = \frac{\sigma_m}{\bar{\sigma}} = \frac{J_1}{\sqrt{3 I_2}} \qquad (5)$$

where σ_m is the mean or hydrostatic stress component and the $\bar{\sigma}$ is effective stress component. The forming limit curve e.g. the curve which shows the first cracks occurrences is defined by this criterion as:

$$\phi_e = f(\beta) \qquad (6)$$

where β can be found experimentally.

The schematic diagram of the proposed forming limit criterion is given in Fig..1. The location of various metal forming operations in the diagram is also shown in the same figure.

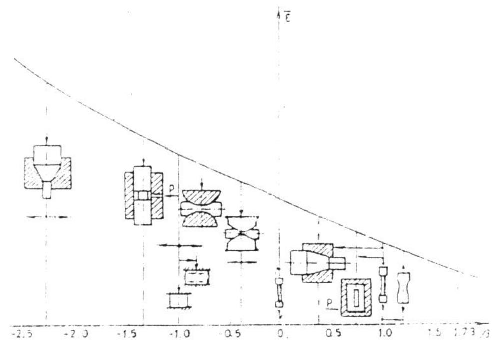

Fig.1. Forming limit curve

Keeler and Backofen /6/ developed the fracture criterion for the sheet metal forming processes. The forming limit diagram by Keeler and Backofen is based upon the major and minor strains (Fig. 2).

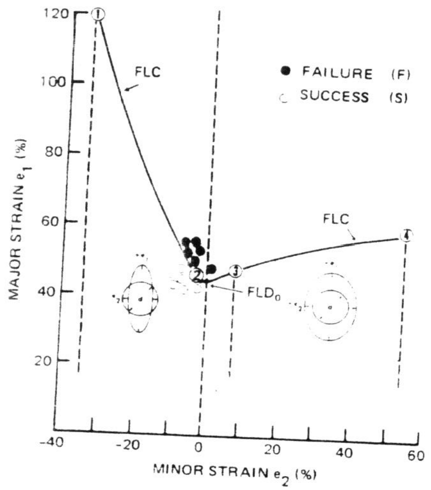

Fig.2. Forming limit diagram for sheet metal forming

3. FRACTURING IN FREE UPSETTING OF CYLINDER

The analysis of the influence of stress state on the formability potential and occurrence of fracture has been made by performing the process of free upsetting of cylinder by flat dies.

In the theoretical case of free upsetting (no friction between the specimen and the die) during the process no barreling of the outer surface occurs. In the real conditions, when friction is present, barreling always appears. The amount of barreling depends on friction conditions on the contact surfaces and on the specimen initial Ho/Do ratio. As far as the first crack occurrence is concerned, the most critical location is the equatorial free surface, where largest barreling takes place.

As shown in /8 /, the stress components σ_Z and σ_T at the equatorial free surface of the specimen can be evaluated as:

$$\sigma_z = \sigma_e \left[1 - \frac{1+2\alpha}{1+\alpha} + \left(\frac{1+2\alpha}{2+\alpha} \right)^2 \right]^{\frac{1}{2}}$$

$$\sigma_T = \sigma_z \left(\frac{1+2\alpha}{2+\alpha} \right) \qquad (7)$$

where σ_e is the effective stress, obtained from the flow curve for the known effective strain, and α is defined as:

$$\alpha = \frac{d\phi_T}{d\phi_z} \qquad (8)$$

The radial stress σ_R at the free surface is zero. The effective deformation can be determined as:

$$\phi_e = \frac{2}{\sqrt{3}} \left(1 + \alpha + \alpha^2 \right)^{1/2} \phi_z \qquad (9)$$

In the present investigation the free upsetting was performed incrementally. As the increments were small enough, the coefficient α can be considered as constant during every single increment. This assumption permits the determination of the stress state at the equatorial free surface at the end of every increment if α is known. The process has been carried out till first crack occurred. At this point the stress components and effective strain were determined, using (7-9).

The knowledge of stress state and effective deformation at the moment of first crack occurrence makes possible the evaluation of one point at the forming limit curve.

4. THE EXPERIMENTAL PROCEDURE AND THE RESULTS

In the experimental investigation the cylinder of initial height Ho=22.10 mm and diameter Do=17.94 mm was incrementally deformed. Before deformation two parallel marks (lines) were put at the equatorial free surface of the cylinder, as shown in Fig. 3.

Fig. 3. The cylinder prior and after deformation

The cylinder was deformed in 6 increments to the final height of 6.22 mm when first crack at the free surface has been detected. After every increment the distance between two parallel lines (Z_i) was measured as well as the equatorial diameter (d_i) and the hight (H_i). This enabled the determination of axial and tangential deformation on the equatorial surface and the coefficient α at the end of every increment:

$$\phi_z = -ln\frac{z_{i-1}}{z_i} \qquad \phi_T = ln\frac{d_i}{d_{i-1}} \qquad \alpha = \phi_T / \phi_z \tag{10}$$

The graphical interpretation of the upsetting in 6 increments is given in Fig. 4.

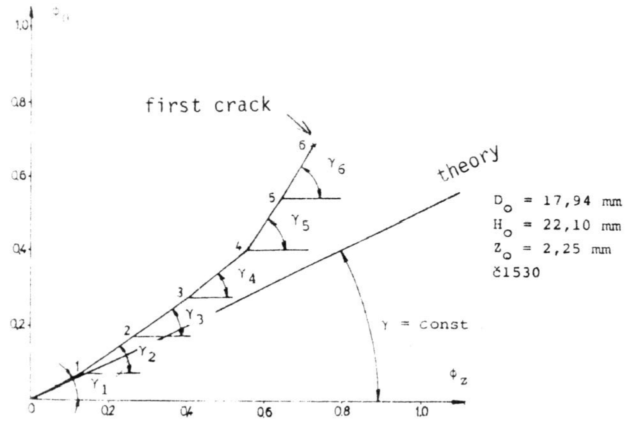

Fig. 4. Upsetting in 6 increments

In the Table 1 the values 1-3 (H_i,D_i,Z_i) were measured, the values 4-9 (ϕ_T, ϕ_z, α, σ_z and σ_T) were calculated using the equations shown above, the value 10 (σ_e) was determined from the known flow curve and value 11 (β) was calculated as:

$$\beta = \frac{\sigma_z + \sigma_T}{\sigma_e}$$

Table 1

H_o = 22,10 D_o = 17,94 Z_o = 2,25

	1	2	3	4	5	6	7	8	9	10	11
	H_i	D_i	Z_i	ϕ_θ	$-\phi_z$	ϕ_e	$-\alpha$	$-\sigma_z$	σ_θ	σ_e	β
1	19,70	19,18	1,97	0,067	0,1329	0,133	0,504	65,80	0,33	66	-0,992
2	16,67	20,99	1,73	0,0928	0,130	0,267	0,713	64,14	21,25	77	-0,557
3	13,79	23,24	1,50	0,102	0,1426	0,414	0,715	69,80	23,35	84	-0,553
4	10,90	26,22	1,29	0,1254	0,1508	0,576	0,836	65,07	37,62	90	-0,306
5	8,13	30,25	1,17	0,143	0,0976	0,722	1,465	22,85	82,46	96	+0,621
6	6,22	34,80	1,08	0,140	0,08	0,862	1,75	9,4	93,95	99	+0,854

The history of deformation at the free equatorial surface is represented by the factor β. This factor is negative at the beginning of the process(compressive stress prevails), whereas at the end of deformation (5th and 6th increment) positive stress component σ_T is larger, so β becomes also positive. This eventually leads to the crack occurrence (Fig. 5).

If the process is analysed in β - ϕ_e diagram, the average value of β has to be estimated. This value can be calculated, according to /9 /, as:

$$\beta_m = \frac{1}{\phi_{ek}} \int_0^{\phi_{ek}} \beta(\phi) d\phi \tag{11}$$

In the present case this average β value is β = - 0,30194.

In the Fig. 5. the history of the process, e.g. the change of β factor during deformation until the first crack is shown as well as the average value of β (point T). In this way one point in the formability diagram has been determined. By changing the friction conditions and the initial specimen ratio Ho/Do it is possible to produce different deformation histories until first crack. In this way more points of the forming limit curve can be determined.

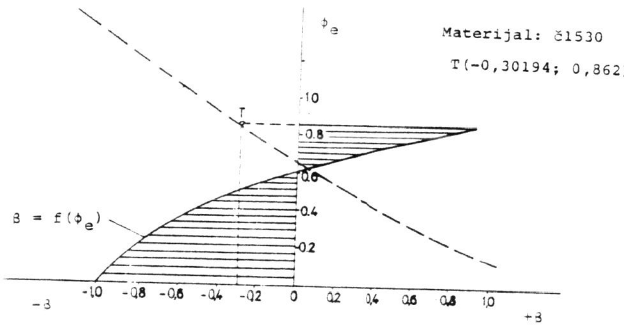

Fig. 5. "History" of the process

5. CONCLUSION

In metal forming processes the occurrence of fracture is one of the limiting factors of application of this technology. Therefore it is essential to create such a process conditions which would prevent the occurrence of fracture at any location of the specimen volume. The forming limit curve gives the information about the stress-strain history, first crack occurrence and their confluences. Generally, when in the deformation zone the tensile stress state prevails, the first crack occurs earlier, whereas the compressive stress components allow for higher degree of deformation without crack.

In this paper the confluences between stress history and first crack occurrence is presented by performing the process of free upsetting of cylinder by flat dies. The process was carried out in 6 increments, till first crack occurred at the free equatorial surface of the specimen. The stress components, effective stress and effective strain were determined for every increment. In this way the "history" of the stress-strain state from the beginning of the process till the first crack occurrence has been determined.

The forming limit curve has to be evaluated experimentally for every single material. The presented procedure enables the determination of the point of this curve in the region between $\beta \approx -1$ and $\beta \approx 0$.

6. REFERENCES

1. S. P. Keeler, W. A. Backofen: "Plastic instability and fracture in sheet stretched over rigid punches", Trans. ASM, Vol. 56, 1963.

2. V. Vujovic, A. Shabaik: "A new workability criterion for ductile metals", J. of Eng. Materials and Technology, Vol. 108, 1988.

3. A. M. Freudenthal: "The inelastic behaviour of solids", Wiley, New York, 1950.

4. S. Ghosh: "A criterion for ductile fracture in sheets under biaxial loading", Metall. Trans. 7A, 523 (1976).

5. M. Oyane T. Sato, K. Okimoto and S. Shima: "Criteria for ductile fracture and their application", J. Mech. Work. Techn. 4, 65 (1980).

6. M. G. Cockroft and D. J. Latham: "Ductility and workability of metals", J. Ins. Metals 96, 33 (1968).

7. S. E .Clift, P. Hartley, C. E. N. Sturgess and G. W. Rowe: "Fracture prediction in plastic deformation processes", Int. J. Mech. Sci., Vol 32, No 1.

8. R.Sowerby,I.O.Reilly,N.Chandrasekaran,N.L Dung:"Materials Testing for Cold Forging" J. of Eng. Materials and Technology, Jan. 1984, Vol. 106.

9. A. D. Tomljenov: "Teorija plasticeskogo deformirovanija metalov", Masinostroenije, Moskva,1972.