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APPLICATION POTENTIAL OF SOME CRITERIA OF DUCTILE CRACK IN BULK FORMING PROCESSES

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ABSTACT: Ductile crack criteria are unavoidable tool for material formability analysis. Their basic task is foreseeing the location of crack occurrence and critical value of deformation level in the course of forming process. However, in order to provide successful application of certain criterion it is necessary to be familiar with material characteristics, specificities of forming processes and forming conditions. For all the above mentioned reasons this paper deals with the analysis of application potential of some widely used criteria of ductile crack in cold bulk forming processes according to representative literature resources. Results can contribute better understanding of phenomenon of material microstructure damage and adequate choice of ductile crack criterion in the analysis of formability in various processes and forming conditions.
Keywords: ductile crack, cold bulk forming, microstructure damage

1. INTRODUCTION

In the course of forming process continuous damage to material microstructure inevitably occurs. Accumulation of critical level happens in the moment of full use of material formability potential which manifests in occurrence of cracks or ductile crack on specimens. In their paper [1], Arentoft et al. provided classification of damage to products obtained in cold bulk forming processes. Experimental research results relating to classification of critical level of accumulated damage in the process of free upsetting of steel cylinder with flat plates with normalized ferrite-pearlite microstructure are presented in [2].

In order to achieve successful design of forming technology it is necessary to use adequate approaches which would enable full use of material formability potential. In that sense, the greatest significance is in ductile crack criteria. Their general purpose is to describe the effects of material damage mechanisms which occur in microscopic level on macroscopic level using experimental data or through mathematical and physical models. Their greatest significance is the ability to forecast the place the crack or fracture would occur in workpiece and estimation of strain limit value.

However, having in mind that bulk forming is performed using various technological methods and under various forming conditions the choice of adequate criterion is very complex. In the literature there are no suggestions about damage critical values for certain materials or the conditions to be fulfilled for using certain criteria. Difficulties arise also in the attempts to establish general strain limit values for the tested material because nucleation of micro voids (the starting point for formation of cracks) and their growth dominantly depend on generated stress state and history of stress state indicators.

In the attempts to overcome the above mentioned difficulties a large number of ductile crack criteria, which with different success rate predicts the occurrence of macroscopic damage on metal components has been developed. Special effort was made in the attempts to analyze and determine possibilities for reliable estimation of initiation and development of material microstructure damage in some forming processes. In majority of papers the above mentioned issue is observed in cold forming processes [3-13], but some data relating to occurrence of ductile crack in forming processes of steel [14] and aluminum alloys [15] in hot state can also be found. Systematic overview of widely used criteria of ductile crack is provided in [16].

In this paper is provided comparative analysis of successful prediction of ductile crack occurrence in the cold bulk forming processes for certain criteria. For the purpose of identification of macroscopic damage in those processes various approaches were used.

2. EXPERIMENTAL – NUMERIC APPROACH

According to the available literature resources, quantitative description of ductile crack formation in cold bulk forming processes research results based on experimental-numeric approach predominantly refer to upsetting and tension processes. Axial-symmetric specimens were mostly used. However, their shape in the starting point had significant influence on initiation of ductile crack [17]. For that reason it is necessary to perform a larger number of tests on specimens with various geometrical configurations prior to including certain parameter of microstructure damage to ductile crack criteria. Nonetheless, that is not an easy task because the difficulties may upraise in the course of theoretical description of three-dimensional material flow from the viewpoint of distribution of stress-strain components.

However, in case of using modified Cockroft-Lathman criterion [16], the impact of stress state on the development of ductile crack may be excluded from the consideration because the critical value of material damage parameter C (1) can be determined only according to identification of strain state on free surface of specimen [18]:

$$2\varepsilon 1 + \varepsilon 2 = 2/3\, C \qquad [1]$$

where: ε_1, ε_2 - components of main strains on the place the crack occurred, C - material constant

On the basis of this result Lyamina et al. presented in paper [19] theoretic-experimental method for verification of the above mentioned criterion of ductile crack. If modified Cockroft-Lathman criterion of ductile crack is valid for the tested material (steel C45E) than the value of parameter C should be equal in all upsetting processes, regardless of the initial shape of the specimens (Figure 1).

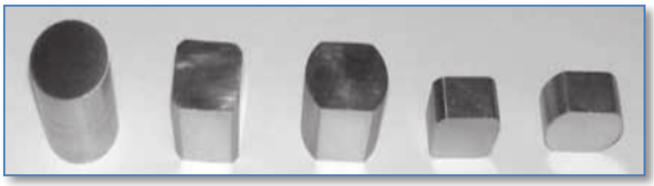

Figure 1. Initial shapes of specimens for upsetting [19]

However, results obtained have shown that the value of parameter C is significantly different for cylindrical (C≈0,7) compared to other types of initial specimen shapes (C≈0,36). For that reason it is stated that modified Cockroft-Lathman criterion is not suitable for tests on steel C45E.

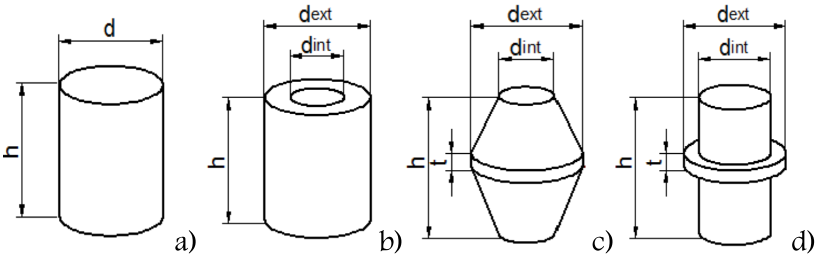

Figure 2. Tested models for upsetting: a) cylinder, b) hollow cylinder, c) tapered specimen, d) cylinder with flanged [20-21]

Gouveia et al. [20] have researched the possibility of successful determination of crack initiation by application of certain criteria under the conditions of plane state of stress. This research was limited to upsetting processes of specimens with various initial shape and dimensions: cylindrical specimens with different h/D ratio, hollow cylinders, tapered specimens and cylindrical specimens with flanged (Figure 2).

Geometric shapes and starting dimensions of models for upsetting shown in Figure 2 enabled generating of different stress-strain state in the destruction zone of the specimen which was a necessary assumption for verification of the potential of tested criteria regarding prediction of location of crack initiation and quantification of material damage parameters. Using Freudenthal, Cockroft-Lathman, Brozzo and Oyane criteria of ductile crack provided prognosis of different locations of cracks and critical values of microstructure damage. In comparison with experimental results it can be noted that Freudenthal criterion is not suitable for the above mentioned forming processes, and possible explanation can be found in the fact that this criterion does not take the level of hydrostatic stress into consideration but only the impact of effective stress to the development of damage of microstructure. Results of numeric analysis according to Cockroft-Lathman criterion of ductile crack are in good accordance with the experimental data but in its application one must take certain observations into consideration. First of all, if the main normal stress σ_1 negative, criterion predicts "negative" accumulation of damage. Secondly, this criterion is not sensitive to changes of main normal stresses which may occur during forming process. On the other hand, using Oyane criterion the above mentioned difficulties are eliminated and due to high level of coherence with experimental results the advantage of its application is additionally stressed for the modeling of surface cracks in cold bulk forming processes.

In the continuation of research the same authors have presented the results of numerical simulations relating to possibility of determination of crack occurrence as well as the deformation level when they occur in the processes of sideways extrusion, forging in open tools and shearing forming in the paper [21]. For those purposes they used Oyane and Cockroft-Lathman criteria of ductile crack. Conclusions affirm the possibility of the tested criteria to successfully determine occurrence of inner cracks and the cracks that form on free surfaces of the specimen. However, the criteria are not able to consider the level of accumulated damage which is a consequence of so called "dead" zones of metal, especially in the process of sideways extrusion. For that reason it is necessary to put extra effort in overcoming the difficulties in modeling shear cracks in processes of shearing forming under the influence of great hydrostatic pressure.

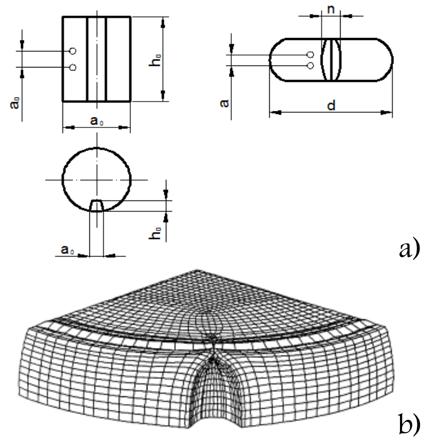

Figure 3. Cylindrical specimens with longitudinal notch: a) initial geometry, b) FEM–final phase [7,11]

Petruška and Janiček [7,11] have also used a large number of criteria of ductile crack in simulations of damage to microstructure under the conditions of increased concentration of stress in upsetting cylindrical specimen with longitudinal notch (Figure 3).

Research was conducted under conditions of changeable friction and with specimens with different h/D ratio. It was experimentally determined that in all the tested specimens the first crack occurred at the top of notch. Results of FEM analysis confirmed that all of the used ductile crack criteria: a) Freundenthal, b) Cockroft and Latham, c) Brozzo, d) Oh, e) Oyane, specifically determine the place of initiation and development of cracks which could be expected regarding the used forming model, but the significant differences occur in the values of load under which the critical microstructure damage occurs. Criteria a) to d) show great variations in estimation of critical load (specimen damage) depending on conditions under which the upsetting test is realized. Results' dissipation is most probably the consequence of different stress state histories at the top of the notch. Only Oyane criterion provides high level of accordance with the experimental data where the results obtained are independent from the conditions of friction and specimen geometry with the exception of the notch depth.

Results of Narayana Murty et al. [10] represent great contribution in the matter of successful prediction of initiation of ductile crack in cold forming processes. Through the experimental research of upsetting the cylindrical specimen under different contact conditions the authors have tested six most frequently used criteria of ductile crack. According to the obtained results new criterion was defined which in this case provides high level of accordance between the experimental data and numeric calculations:

$$\mathrm{Dth} = \int_0^{\varphi^{l}{}_{e}} \gamma \frac{\sigma\theta}{\sigma e} + \delta \frac{\sigma H}{\sigma e} d\varphi e = 1 \quad (2)$$

Material constants γ and δ can be determined according to values of forming limits φ_θ^l and φ_z^l. ductile crack criterion, defined by equation (2), basically represents a combination of Oyane and Oh-Kobayashi criteria which achieved the best results in individual tests. Higher possibilities of the new criteria regarding more precise determination of ductile crack initiation are a consequence of more complex approach to the analysis of impact of stress state character to the development of microstructure damage.

In the research presented in paper [22], using certain number of ductile crack criteria, comparison analysis of possibility of adequate prediction of location of crack initiation in two forming models was performed (Figure 4).

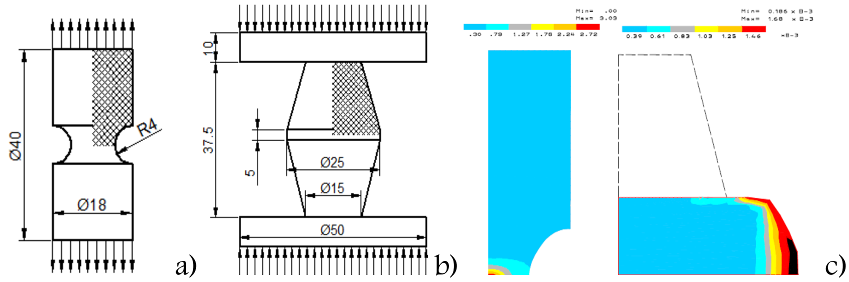

Figure 4. Tested forming models and MKE analysis: a) tension of grooved specimen, b) upsetting of tapered specimen, c) visualization of MKE results – crack criterion based on the theory of continuum damage mechanics [22]

The first model relates to the process of tension of grooved specimen where the maximum value of effective plastic strain is achieved at the place where the cross section narrows but the crack itself is initiated in the center of specimen where the ratio of hydrostatic and effective stress reaches maximum value. The second model is based on the test of upsetting the tapered specimen with flat plates. In this case the initiation of the crack occurs on the outer surface of the specimen close to the equatorial section due to generating of tension components of stress. The choice of models is conditioned with the aspiration to test the crack criteria under the conditions where stress state has different character of action to the development of microstructure damage and occurrence of crack.

Results of experimental-numeric research point to the different abilities of tested criteria in terms of predicting the location of initiation of ductile crack. Criteria based on total work of plastic forming (Freudenthal) and effective plastic strin (Datsko) provide very poor prognosis of place of ductile crack initiation in both forming models. Criteria based on the enlargement of damage to microstructure due to action of main stresses (Cockroft and Lathman, Brozzo et al.), provide correct prediction for initiation zone of ductile crack for upsetting test, but in very wide area. However, that is not the case in tension test where the adverse ratio of hydrostatic and effective stress makes the main reason for microstructure damage.

Ability to predict the location of crack using the criteria based on dominant impact of hydrostatic stress to increase in level of microstructure damage (Norris, Atkins) in researched forming models is disappointing. This fact states that hydrostatic stress being very influential factor for initiation and development of damage, in the process of prediction of crack initiation it cannot be used on its own while defining the criteria of material ductile crack [22]. Oyane criterion provides precise prediction of crack initiation in both tested forming models but in very wide area. Criterion Lemaitre, which was developed according to the mechanics of continuum damage, provides successful prediction of location of crack occurrence in tension test but not in upsetting test. Also, the criterion suggested by Vaz has almost identical result as prediction criterion of Lemaitre. Very precise prediction of crack location in both processes of forming was achieved only by using the criteria suggested by Pires et al. (Fig. 2c). This criterion is actually a modification of Lemaitre's criterion taking in consideration the effect of closing the micro voids which enables different treatment of microstructure damage development in the processes with dominant tension or pressure stress state.

3. HOLISTIC APPROACH

In the past a number of elite criteria for estimation of damage to material microstructure in the processes of cold bulk forming was developed and majority of them is incorporated in commercial FEM applications. The most widely exploited criteria are ones of ductile crack defined according to the theory of continuum damage mechanics. Their basis is represented by integral formulations determined between individual stress-strain components which enable the calculation of theoretical level of microstructure damage. However, none of the criteria presented in paper [16] provides absolutely defined possibility to predict the exact initiation of crack occurrence with high reliability, the level of microstructure damage as well as the type of crack in different forming processes. Incorrect prognosis are a logical consequence of not taking into consideration time differences in initiation and growth of micro-fractures as well as phenomenological differences in crack types [23].

In order to overcome the above mentioned shortcomings, Kloske [23] and Timmer [24] suggested the criterion for the processes of cold bulk forming which is based on holistic approach of initiation and development of ductile crack. The criterion enables predictions regarding spatial position of the point of crack initiation, moment of accumulation of critical microstructure damage depending on level of strain and crack type. Modeling of damage depends on the length of initiation and development (growth) of micro-voids including the identification of mechanism of damage and corresponding stress-strain state for longitudinal or shear surface cracks. For the development of this model were used various tests of upsetting the specimens with different initial geometry. Upsetting was realized until any type of crack occurred on the outer surface of the specimen (Figure 5). The results obtained were presented with characteristic differences between time-dependent micro-models for each type of the crack.

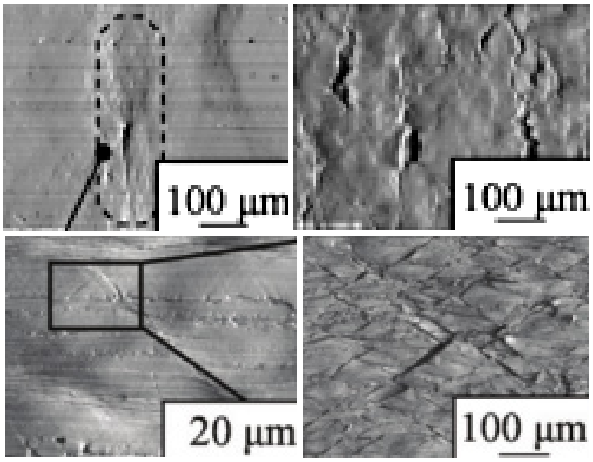

Figure 5. Types of crack on outer surface: a) initiation and growth of longitudinal cracks, b) initiation and growth of shear cracks [24]

Analyzing the stress state on the outer surface of the specimen it was determined that the component of normal stress in tangential direction σ_θ has the most dominant influence on initiation and development of longitudinal crack. So, longitudinal cracks are initiated when the amount of energy, which is induced in the material due to the action of σ_θ stress component, reaches critical value which is considered constant for certain material.

In Figure 6 is presented the concept of micro-model of initiation and growth of longitudinal cracks. Positive values of σ_θ and negative values of axial component of stress σ_z make the cracks open. Opposite from that, negative values of σ_θ and positive values of σ_z influence the closure of cracks and mitigate the level of microstructure damage.

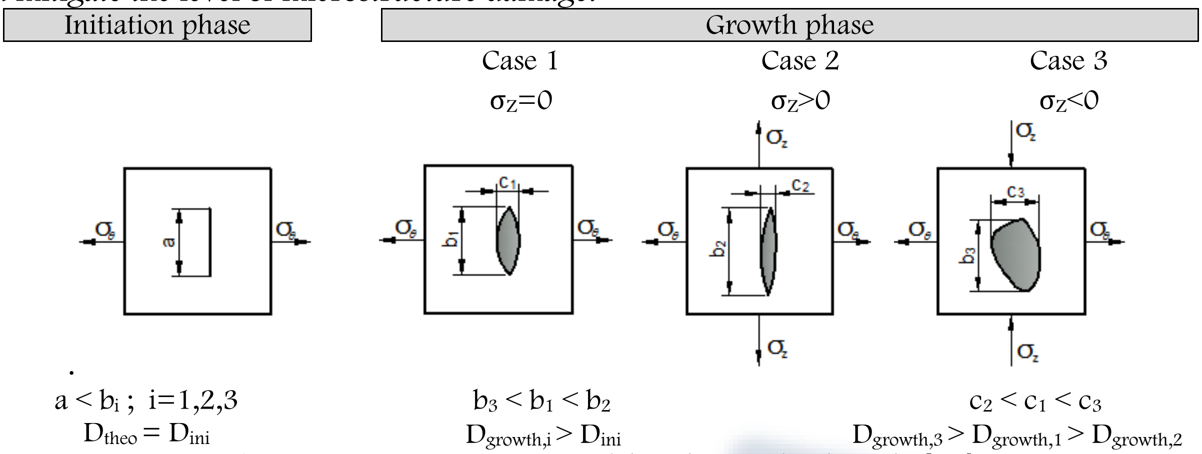

Figure 6. Concept of micro-model for longitudinal cracks [23]

According to micro-concept a sub-criterion for longitudinal ductile crack was formulated (3), whose basic characteristic is time differentiation of phases of initiation and growth of cracks.

$$D_{theo,LC} = \underbrace{\int_{0}^{\varphi_{eff,Inic}} \max\left(0, \frac{\sigma_\theta}{\sigma_v}\right) d\varphi_{eff}}_{Initation} + \underbrace{\int_{\varphi_{eff,Inic}}^{\varphi_{eff,end}} \left(\frac{\sigma_\theta}{\sigma_v} \cdot \left[\begin{array}{l} \sigma_z \succ 0 : \left| \dfrac{\sigma_{z,Inic}}{\sigma_z} \right| \\ \sigma_z \prec 0 : \left| \dfrac{\sigma_z}{\sigma_{z,Inic}} \right| \end{array} \right] \right) d\varphi_{eff}}_{Growth} \qquad (3)$$

It was determined through identifying the stress state on surface sections of the specimens for initiation phases and development of shear cracks that this type of cracks occurs due to the action of maximal tangential stress $\tau_{\theta z,max}$. On the critical location of specimen free surface other identified stress components had negative or negligible small positive values. Maximum tangential stress $\tau_{\theta z,max}$ has the highest value, except in the end of crack growth phase, which promotes it as the most dominant factor in initiation and growth of shear cracks. Concept of micro-model of initiation and growth of horizontal cracks is presented in Figure 7.

Mathematical formulation of the previous model provides the concept of time differentiation of initiation phase and growth of shear cracks in defining the sub-criterion of ductile crack:

$$D_{theo,SC} = \underbrace{\int_{0}^{\varphi_{eff,Inic.}} \frac{\left|\tau_{\theta z,\max}\right|}{\sigma_v} d\varphi_{eff}}_{Initiation, D_{Inic.}=0{,}1791} + \underbrace{\int_{\varphi_{eff,Inic}}^{\varphi_{eff,end}} \left(\begin{cases} \sigma_m \geq 0 : \dfrac{\sigma_m + \left|\tau_{\theta z,\max}\right|}{\sigma_v} \\ \sigma_m \prec 0 : \dfrac{\left|\tau_{\theta z,\max}\right|}{\sigma_v} \end{cases} \right) d\varphi_{eff}}_{Growth, D_{Gro}} \quad (4)$$

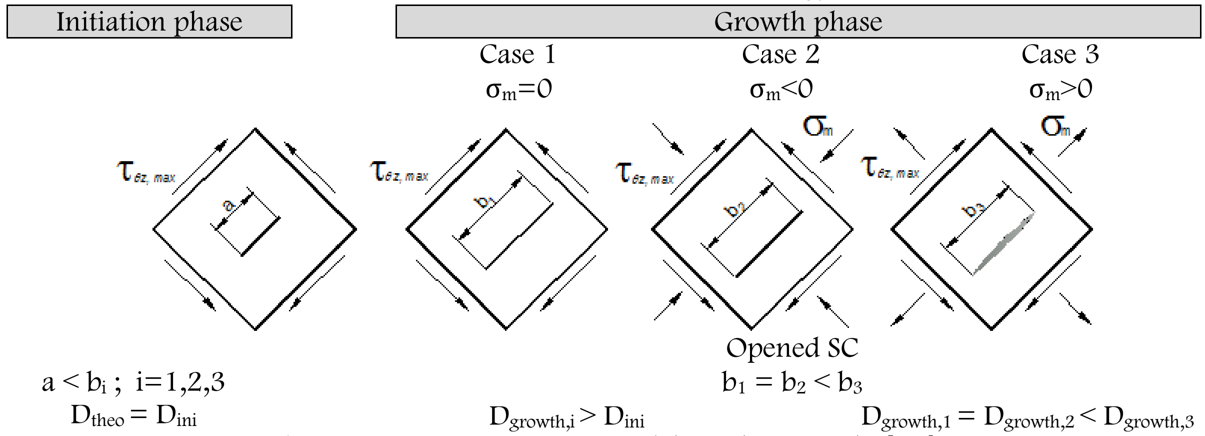

Figure 7. Concept of micro-model for shear cracks [23]

Generally speaking, research results show that the suggested sub-criteria provide greater reliability of prediction of exact moment the ductile crack occurs in comparison to previously used approaches and mathematical formulation. Synthesis of both sub-criteria with the aim of defining the comprehensive criterion of ductile crack as well as the final verification is the following research challenge.

CONCLUSION

It is obvious that the criteria of ductile crack together with the formability tests present extremely useful tool regarding the optimization of the technological forming process. Considering the fact that there is no unified criterion of ductile crack which can be applied to all materials, it is necessary to verify its application to the specific material experimentally and under specific processes and forming conditions. That means that it is necessary to identify one or more criteria which are in accordance with the experimental data. Such task is impossible to accomplish without the use of powerful numeric methods (generally represented by FEM), on the basis of which special program packs for material formability analysis are developed. Therefore, only the integrated approach is the promising technique for the success in the area of prediction of occurrence of ductile crack in the forming processes.

Note: This paper is based on the paper presented at The Vth International Conference Industrial Engineering and Environmental Protection 2015 – IIZS 2015, University of Novi Sad, Technical Faculty „Mihajlo Pupin", Zrenjanin, SERBIA, October 15-16th, 2015, referred here as[25].

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