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VARIOUS APPROACHES TO DEFINING THE CRITERIA OF DUCTILE CRACK IN COLD BULK FORMING PROCESSES

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Abstract: In the process of metal forming continuous development and accumulation of material microstructure damage takes place. Reaching the critical level of damage, macroscopic damages occur which is manifested by crack and destruction of specimen (i.e. the crack) in metal forming processes. Optimal and rational design of technological forming processes means recognizing the location the crack occurs and strain limiting value. The ductile crack criterion is used for the purpose of solving this very complex task of material formability. In this paper we provided overview of theoretical and experimental approaches used for the purpose of defining the criteria of ductile crack based on reference literary resources.
Keywords: ductile crack, cold bulk forming, damage microstructures

1. INTRODUCTION

In the metal forming process various types of microstructure damage occur, and with the increase of forming level they take macroscopic proportions. Generally speaking, macroscopic damage occurs during forming in cases when properties of metal components are not in line with specific features of construction solution and designed technological process. There are many reasons why they occur: a) wrong choice of material which includes chemical composition, microstructure state, volume content of microstructural constituents, presence of non-metal included materials and other secondary phases, size of crystal grain, mechanical and physical characteristics, history of thermal treatment, b) inadequate defining of forming conditions and parameters (number and sequence of operations, forming temperature, strain rate, non-technological properties of the product, tribological aspects, mechanical processing of the workpiece, state of tools (geometrical precision and adequate thermal processing), state of equipment regarding precise positioning of tools and workpiece etc. Types of macroscopic damage in forming processes are provided in the study by Arentoft et al. [1]. Nevertheless, the most common type of material damage in bulk forming processes are cracks formed on free surface of the specimen and internal cracks.

From the standpoint of production, occurrence of cracks and breaks is very negative feature, except in certain forming processes where it is necessary for realization of certain operation with the final aim of obtaining products with certain demanded characteristics (for instance, production of seamless tubes etc.). On the other hand, in general terms, in case ductile crack occurs, any further forming has to be stopped and that makes it main limiting factor to increase in productivity in metal forming processes.

Possibility to predict location on the workpiece and level of strain at which the initiation and development of ductile crack occur has very important role in optimal projecting of technological processes in metal forming. Experimental research has validated that mechanisms of nucleation, growth and coalescence of micro-voids which control the level of microstructure damage and lead to activation and expansion of the crack are under the influence of various factors out of which the largest influence is presented by state of stress in the critical forming zone.

Based on the available literature, in this paper are systematically presented some of the most commonly used criteria of ductile crack which are used for the purpose of predicting the exact location of critical damage to microstructure and forming limit in cold bulk forming proceses. Various approaches used for the mathematical formulation of the processes are also used in the course of the paper.

2. THEORETICAL ASPECTS OF DEFINING DUCTILE CRACK CRITERIA

It is common fact that there is large number of criteria which in various ways presents the possibility of detecting critical level of damage to microstructure with the aim of detection of initiation of crack or ductile crack available in scientific literature. Term damage or degradation is used here in the sense of deterioration of possibility of material microstructure to take load during forming process. Ductile crack criteria have the purpose to describe material damage that occurs on macroscopic level using experimental data or through mathematical and physical models. Their basic aim is to predict the location of occurrence of the crack and critical value of forming level during specific forming phase. In the meanwhile, it is necessary to define the parameter which describes the intensity of damage and which reaches its maximum value in the moment the crack occurs.

Nevertheless, it is clear that critical value of damage which can be defined as total accumulated damage to microstructure until the moment the unwanted forming occurs at the critical location of the metal component varies depending on the forming process applied, the forming conditions and material used. In the literature there are no available suggestions for critical values of damage for the specific material nor the conditions to be fulfilled while using certain criteria. Difficulties also occur while trying to establish general values of limit strains for the tested material because nucleation of micro-voids (the start point of crack forming) and their growth predominantly depend on generated stress state and history of stress state indicators.

It is generally accepted that while defining the ductile crack criteria we have to take into consideration the following [2]:

» Strain path (history of stress state indicators) because currently generated stress state is not sufficient to characterize the level of material's level of microstructure damage,
» Hydrostatic stress, considering the fact that material formability is very sensitive to variations of σ_H,
» Adequate ratio of σ_H/σ_e, making plasticity and level of damage to microstructure easier to be more comprehensively described.

In the general case, function of damage to material microstructure D_{th} can be described in the implicit form [2-4]:

$$D_{th} = \int_0^{\varphi_e^g} f\left(\sigma_H(t), \sigma_e(t), \varphi(t), \dot{\varphi}(t), \ldots\right) d\varphi_e \rangle D_{th,cr.} \tag{1}$$

where: σ_H – is hydrostatic stress, σ_e – is effective stress, φ – is logarithm strain, $\dot{\varphi}$ - is strain rate, φ_e^g – is limi value of effective strain, $D_{th,\,cr}$ –is critical value of material microstructure damage.

According to equation (1), the crack in the material starts to develop when calculated value of damage D_{th} is larger than critical value $D_{th,cr}$.

With the respect to recognizing the complexity of this issue various criteria of ductile crack have been developed in the past. Their models of damage to material's microstructure can be divided into two groups. The division was performed depending on approach used in their defining [5]:

» Uncoupled approach – damage models are described in the manner to indirectly, through values of certain process parameter during various numerical analysis, influence material properties. Ductile crack criteria whose formulation is based on the energy needed to establish limit strain and models where material's damage to microstructure occurs due to nucleation, growth and coalescence of micro-voids are used in this approach.
» Coupled approach – damage models in forming process progressively take into consideration level if damage to microstructure material strength. In that process output values of every consequent numeric iteration depend on value of current damage to microstructure or history of indicators of stress state. In this group are the criteria based on porosity theories and continuum mechanics.

According to the available literary resources [2-3, 5-13], in the following paragraphs is provided overview of ductile crack criteria which provide prognosis of the place the crack occurs in the material and strain level at which critical damage occurs with different level of success.

3. DUCTILE CRACK CRITERIA BASED ON CUMULATIVE ENERGY OF METAL FORMING PROCESS

One of the earliest attempts to define ductile crack criteria is based on the assumption that initiation and expansion of the crack occurs at critical value of energy absorbed in the process of metal forming - Freudenthal (1950.):

$$D_{th} = W_p = \int_0^{\varphi_e^g} \sigma_e \, d\varphi_e \tag{2}$$

where: W_p – specific work of deformation, σ_e – effective stress, φ_e^g – limit value of effective strain at the place the crack occured.

Criteria suggested by Datsko (1966.) suggests that activation of the crack occurs when effective strain reaches critical value. Criteria is mathematically formulated in the following form:

$$D_{th} = \varphi_e^g = \int_0^{\varphi_e^g} d\varphi_e \tag{3}$$

Criteria suggested by Cockroft and Latham (1968.) assumes that the most relevant impact on initiation of the crack is influence of main normal stress σ_1, or critical value of energy spent per volume unit in the process of workpiece tension:

$$D_{th} = \int_0^{\varphi_e^g} \sigma_1 \, d\varphi_e \tag{4}$$

where: σ_1– is maximum normal stress.

Ct that there is limited number of cases where criteria (4) enables reliable prediction of crack, Oh and Kobayashi suggested normalized version where stress state does not possess purely tension character:

$$D_{th} = \int_0^{\varphi_e^g} \frac{\sigma_1}{\sigma_e} d\varphi_e \tag{5}$$

Later on Brozzo, De Luca and Rendina (1972.) modified the criteria (5), defining its explicit dependence on the function of maximum normal stress σ_1 and hydrostatic stress σ_H:

$$D_{th} = \int_0^{\varphi_e^g} \frac{2\sigma_1}{3(\sigma_1 - \sigma_H)\sigma_e} d\varphi_e \tag{6}$$

Norris et al. (1978) suggested empirical system based on the influence of hydrostatic stress to development of cracks in the following form:

$$D_{th} = \int_0^{\varphi_e^g} \frac{1}{(1 - c_N \sigma_H)} d\varphi_e \tag{7}$$

where: c_N – is a constant depending on type of material.

When it was determined that criteria (7) did not have the potential to provide reliable prediction of occurrence of crack in processes of deep drawing and forging, Atkins (1981), introduced explicit dependence of ductile crack indicator values from strain path in defining the new criteria:

$$D_{th} = \int_0^{\varphi_e^g} \frac{1 + 1/2\alpha}{(1 - c_A \sigma_H)} d\varphi_e \tag{8}$$

where: $\alpha = \frac{d\varphi_1}{d\varphi_2}$ – is main strains accession ratio; c_A – is constant depending on the material.

4. DUCTILE CRACK CRITERIA BASED ON MODEL OF GROWTH AND COALSCENCE OF MICRO-VOIDS

Nucleation, growth and coalescence of micro-voids are considered to be main reason for occurrence of ductile crack in metal forming processes. Criteria inspired by this hypothesis can be based on various physical aspects like geometry of micro-voids, nucleation mechanism and micro-voids growth mechanism or model of material constitution.

McClintock (1968.) was one of the first researchers who defined the criteria of ductile crack for cylindrical micro-voids with parallel orientation in relation to tension stress axis using the above mentioned approach:

$$D_{th} = \int_0^{\varphi_e^g} \left\{ \frac{\sqrt{3}}{2(1-n)} \sinh\left[\frac{\sqrt{3}(1-n)}{2} \cdot \frac{\sigma_a + \sigma_b}{\sigma_e} \right] + \frac{3}{4}\left(\frac{\sigma_a - \sigma_b}{\sigma_e} \right) \right\} d\varphi_e \tag{9}$$

where: σ_a and σ_b – are main stresses in direction of extreme values of micro-void strain, n – hardening coefficient

Equation (9) defines critical level of damage to microstructure caused by merging of micro-voids into macro-void in the process of metal forming on the part of material characterized by plane strain.

Guided with the results of previous research, Rice and Trasey (1969) established more realistic criteria of ductile crack according to the analysis of increment growth of spherical micro-voids taking into consideration ratio of hydrostatic and effective stress, i.e. interaction and unstable coalescence of neighboring voids. The criterion is defined in the following form:

$$D_{th} = \int_0^{\varphi_e^g} A \cdot exp\left(\frac{3\sigma_H}{2\sigma_e} \right) d\varphi_e \tag{10}$$

where: A – is material constant which is experimentally determined.

Assuming that in the metal forming process generating, increment growth and coalescence of micro-voids occurs which leads to final material destruction, Oyane et al. (1978. i 1980.) developed ductile crack models for compact and porous materials. In case of compact material criteria of ductile crack is presented in the following relation:

$$D_{th} = \int_0^{\varphi_e^g} \left(1 + \frac{\sigma_H}{A\sigma_e} \right) d\varphi_e = C \tag{11}$$

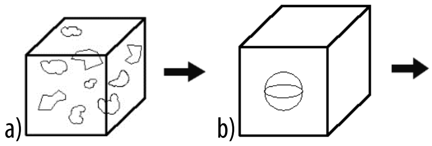
where: A and C – are constants depending on type of material and they are experimentally determined.

Value of effective strain in the moment the crack occurs is determined according to the expression (12):

$$\varphi_e^g = -\frac{1}{A}\int_0^{\varphi_e^g}\left(\frac{\sigma_H}{\sigma_e}\right)d\varphi_e + C \tag{12}$$

5. DUCTILE CRACK CRITERIA BASED ON THEORY OF POROSITY

According to the theory of material porosity, change in density can be advantageous parameter for characterization of material damage. Gurson [14] was one of the first researchers who defined the ductile crack criteria based on porosity concept. Observing the material as porous medium where the impact of stress-strain state and the flow forming to nucleation and growth of micro-voids cannot be neglected, he defined scalar measurement (f) as a ratio of average volume of micro-voids and total volume of material which actually represents volume value of micro-voids in the material (Figure 1). Primary concept of describing porous properties of material is based on this assumption, where internal variable f is used for characterization of damage to microstructure.



$$f = \frac{dV_{voids}}{dV_{cells}}$$

Figure 1. Gurson's model: a) material porosity, b) average measure of fraction of micro-voids [14]

Gurson's model idealizes the actual distribution of generated micro-voids in unit aggregate of material through one spherical micro-void (Figure 2.).

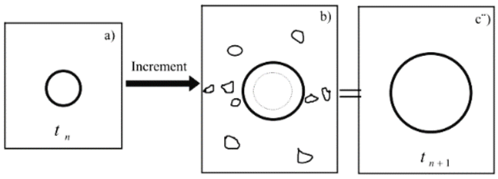


Figure 2. Gurson's model – graphical interpretation of nucleation and increment of micro-void [14]

Using the upper bound method, Gurson defined the function of plasticity potential which depends on fraction of micro-voids (13):

$$\Phi = \frac{\sigma_{ef}^2}{\sigma_M^2} + 2f\cosh\left(\frac{3\sigma_m}{2\sigma_M}\right) - 1 - f^2 = 0 \tag{13}$$

where: f – is fraction of micro-void (Figure 1.), σ_m – is mean normal stress, σ_{ef} – is conventional effective stress (von Mises), σ_M – is flow stress.

From the equation (13) is obvious that with the increase in damage to microstructure the reduction in flow stress occurs. For the compact material (f=0), Gurson's model is identical to conventional von Mises' model.

In its core, oroginal Gurson's model mathematically interprets continuous process of damage to microstructure with the increase of fraction of micro-voids, where total loss of flow stress can occur only if the fraction of micro-voids reaches theoretical final value, i.e. when $f=100\ \%$. Such possibility is not realistic because in physical sense material should completely disappear.

In order to take into consideration effect of coalescence of the neighboring micro-voids to occurrence and growth of the crack Tvergaard and Needleman [15] conducted the modification of Gurson's model of microstructure damage. Gurson-Tvergaard-Needleman (GTN) model has a goal to enable modeling of nucleation, growth and coalescence of micro-voids mechanism through accumulated damage to microstructure. It is based on hypothesis that micro-mechanical characteristics of development of ductile crack can be macroscopically described by addition to von Mises' theory of plasticity taking into consideration effects of porous properties of the material.

Unlike Gurson, who models porous properties in the material through fraction of one single isolated micro-void, Tvergaard and Needleman represent the change of volume content of micro-voids in the material in a form dependant of nucleation of new micro-voids, but also of effect of growth of the existing ones[14-16]:

$$\dot{f} = \dot{f}_{nukleacija} + \dot{f}_{rast} \tag{14}$$

$$\dot{f}_{nukleacija} = A\dot{\varepsilon}_M \tag{15}$$

$$\dot{f}_{rast} = (1-f)\dot{\varepsilon}_{kk} \tag{16}$$

where: A – is function of effective strain for fully compact material ε_M, defined in such manner that distribution of generated micro-voids responds to normal division, ε_{kk} – is strain tensor representing the change in volume.

Modified equation (13) represents mathematical representation of GTN model (17):

$$\Phi=\frac{\sigma_{ef}^{2}}{\sigma_{M}^{2}}+2q_1 f^{*}\cosh\left(\frac{3q_2\sigma_m}{2\sigma_M}\right)-\left[1+\left(q_1 f^{*}\right)^{2}\right]=0 \tag{17}$$

GTN model predicts that describing of ductile crack takes place through fraction of micro-voids f^{*} which takes into consideration the effects of coalescence, and two constants for the material, q_1 and q_2. Function of fraction of micro-voids f^{*} is defined with the following expression:

$$f^{*}=\begin{cases} f & za\, f\leq f_c \\ f_c+\left(\dfrac{1/q_1-f_c}{f_f-f_c}\right)\left(f-f_c\right), & za\, f_c\prec f\prec f_f \end{cases} \tag{18}$$

where: f_c –is critical fraction of micro-voids – reaching the value f_c coalescence starts, f_f – fraction of micro-voids at the moment the crack occurs.

6. DUCTILE CRACK CRITERIA BASED ON THEORY OF CONTINUUM MECHANICS

Generally speaking, ductile crack criteria (variables of microstructure damage) are defined according to constitutive equations for the damaged material considering certain specific traits of dominant mechanisms of growth and nucleation of micro-voids. In this part of paper we analyzed the aspects of application of this approach in the area of defining the criteria of ductile crack. In the course of process are avoided rigorous mathematical formulations.

Starting from the schematic overview of the model of damaged material, Lemaitre [2, 5, 9], (Figure 3.) defined the variable of damage to microstructure where size of representative element of volume on micro level is large enough to contain a lot of damage but small enough to be considered material point in continuum mechanics with the following equation:

$$D=\frac{A_{voids}}{A_0}=1-\frac{A_{ef}}{A_0} \tag{19}$$

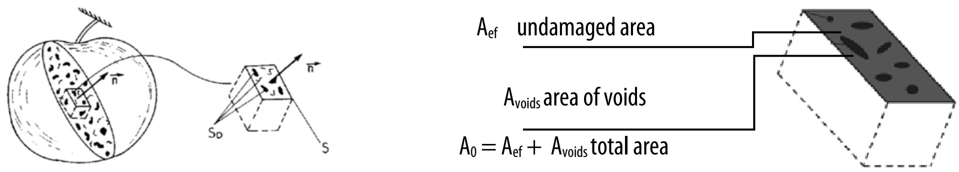


Figure 3. Representative element of volume of damaged material [5]

When material is not damages value of variable is D=0, and when ductile crack occurs its critical level is reached $D=D_C$ ($0,2 \leq D_C \leq 0,8$ – for metal materials). If value of damage variable is available than in a specific case it is possible to determine equivalent stress by calculating the nominal stress σ, as a measure of force effect to the entire area A_0:

$$\sigma_{ef}=\frac{\sigma}{1-D} \tag{20}$$

According to Lemaitre [5], constitutive equations of damaged material are identical to equations for undamaged material where nominal stress is replaced with equivalent stress. Characteristic examples are equations in the area of linear elasticity:

$\varepsilon=\dfrac{\sigma}{E}$ - undamaged microstructure; $\varepsilon=\dfrac{\sigma_{ef}}{E}=\dfrac{\sigma}{E(1-D)}$ - damaged microstructure.

For characterization of ductile crack Lemaitre suggested criterion based on critical amount of elastic energy released from damage material microstructure (Y_c), [2]:

$$-Y_c=\frac{\sigma_{ef}^{2}}{2E(1-D)^{2}}\left[\frac{2}{3}(1+\nu)+3(1-2\nu)\left(\frac{\sigma_M}{\sigma_{ef}}\right)^{2}\right] \tag{21}$$

Analyzing Lemaitre criterion for ductile crack from the aspect of adequate energy use in process of predicting the location of critical damage, Vaz et al. [17] suggested the indicator of ductile crack based on total work done on damaged microstructures. Pires et al. [11] modified the previously mentioned criterion so it took into consideration the impact of closing the micro-cracks under the influence of pressure components of stress. In this criterion, amount of released energy from the place the critical damage occurred is expressed through main stress which enables the ability that using the parameter of closing the micro-voids, the development of damage for tension and pressure states would be treated differently.

7. CONCLUSION

Issue of defining the criteria of ductile crack is very complex area of research in formability. For that reason various theoretical and experimental approaches were used in the past for description of development and accumulation of critical level of damage to material microstructure in metal forming processes. According to the available literary resources, in this paper is analyzed the state of contemporary research in this area. From it we can draw following conclusions:

- Criteria of ductile crack whose mathematical interpretation is based on the amount of accumulated energy in the forming process are mostly defined according to research results about specific processes of metal forming. Implementation of such approach in numeric simulations is relatively simple and fast, but precise predictions about the moment (level) and place of deformation can not be achieved unless the realization of forming process is performed under conditions identical to the ones where certain criterion was defined. If the history of stress-strain state is different from the referential values, the criteria is not able to predict the exact spot where the crack occurs.
- Regardless of the simplified representation of growth in micro-voids due to plane stress state, McClintock's forming model has the potential to describe the level of damage through numerous experimental conditions and provide insight into certain findings regarding the impact of ratio (σ_H/σ_e), flow stress and history of stress-strain state to the development of ductile crack.
- Oyane's criterion of ductile crack is advantageous for application in various conventional metal forming processes, therefore it is incorporated in a large number of commercial numeric applications.
- Regardless of the simplification in using the numeric procedure, it is assumed that micro-voids do not interact, which is the basic limitation to Gurson's model. Specifically, model of ductile crack which Gurson suggested does not allow modeling of the final phase of increment growth when the coalescence of voids occurs due to local stress.
- Modification of Gurson's which takes into consideration the effects of merging neighboring micro-voids to occurrence and increment of crack is defined in GTN model. On the basis of these results a lot of research has been conducted which validated the ability of GTN model to successfully predict the development of damage and ductile crack in metal materials.
- Characterization of damage to material microstructure based on the application of continuum mechanics theory is a powerful and reliable approach to successful prognosis of initiation and development of ductile crack. In such manner the integral approach to the research of this matter is made possible because effects of progressive damage to the material to its properties in the forming process ae taken into consideration. Although the calculus is challenging, criteria of ductile crack based on theory of continuum mechanics enable analysis of complex strain paths which provides better approximation of realistic forming process and gaining of more reliable prognosis.
- Although there are great scientific advancements in this area, it is common opinion that there is no unified and universal approach which can comprehensively describe all the conditions under which ductile crack occurs in the metal forming processes.

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