ANNALS of Faculty Engineering Hunedoara
– International Journal of Engineering
Tome XV [2017] – Fascicule 2 [May]

ISSN: 1584-2665 [print; online]
ISSN: 1584-2673 [CD-Rom; online]
a free-access multidisciplinary publication
of the Faculty of Engineering Hunedoara

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SOME ASPECTS OF DEVELOPMENT OF DUCTILE CRACK IN THE PROCESS OF COLD BULK FORMING

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Abstract: The main limiting factor in increasing the productivity of the process of cold bulk metal forming is the appearance of plastic fracture. However, proper design of a technological process can greatly increase formability of the material. For those activities it is necessary to fully understand all the factors that affect constituent stages of development and the appearance of macroscopic damage on metal components. Therefore, based on the available literature resources and our own research, the impact of the most dominant factors on accumulation of critical damage of microstructure in cold bulk metal forming processes with special reference to the impact of stress state was analyzed in this paper.
Keywords: Ductile crack, stress state, cold bulk forming

1. INTRODUCTION

Plastic metal forming technology represents a very important and very broad technological area of production engineering. It is actually a highly productive technology which integrates a larger number of technological methods for obtaining metal components for a wide range of applications. According to relevant data [1], more than 80% of metal materials, in certain phases of processing, are being treated with some of the many technological processes of plastic forming.

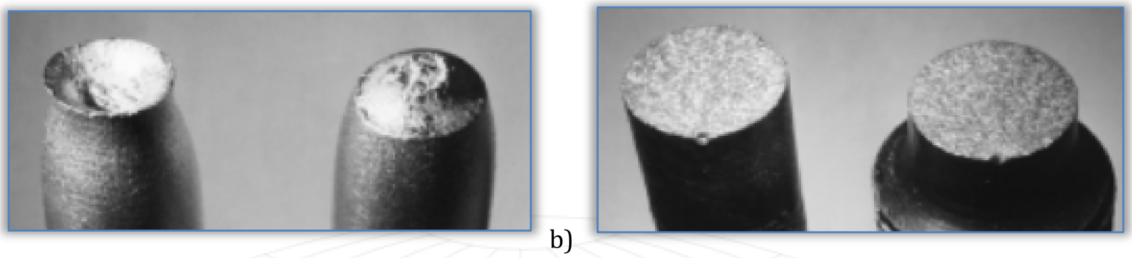
The main characteristic of any deforming process is continuous change of the stress-strain state in order to obtain the required shape and dimensions of the working part. These changes usually lead to worsening conditions of processing, which is manifested by reduced formability potential of materials. The effects can be mitigated by appropriate choice of materials, heat treatment and design of manufacturing systems with the prevailing compressive stress in the forming zone. However, no matter what measures are taken, forming inevitably leads to the development of micro-structural damage. When the level of accumulated microstructure damage reaches a critical level, macroscopic defects can be observed on the workpiece that limit further processing of metals. In cold bulk forming the occurrence of plastic fracture is considered to be the main limiting factor for the continuation of production.

No matter that the phenomenology of initiation and development of plastic fracture of metal components represented a challenge for many researchers in the past, this issue still draws attention of scientific experts. It is known that a great deal of effort was invested to understand constituent phases of plastic fracture. In doing so, different approaches were used. A short review of mathematical description of the appearance of plastic fracture is shown in [2], and [3] analyzes the application possibilities of some criteria of plastic fracture. Also, extensive results are published in terms of quantification of microstructural damage and identification mechanisms of nucleation, growth and coalescence of microvoids, as initial forms of material destruction [4-6]. However, studies in the past have mainly focused on the forming process dominated by tensile stress components. On the other hand, there are also studies that deal with the issue of development of plastic fracture, quantification of microstructural damage and level of forming of the microconstituents in the process of upsetting [7-8].

Due to the complexity of the issues explored, the remaining part of this paper considers constituent phases of the development of plastic fracture with special attention to the factors that lead to initiation of various mechanisms of microstructure damage. In this respect very significant results may be those that will contribute to a better understanding of the impact of stress state on the occurrence of plastic fracture, taking into account the fact that it is possible to design machining systems that will stimulate the realization of a higher range of limit strain.

2. A SHORT REVIEW OF GENERAL CONSIDERATIONS

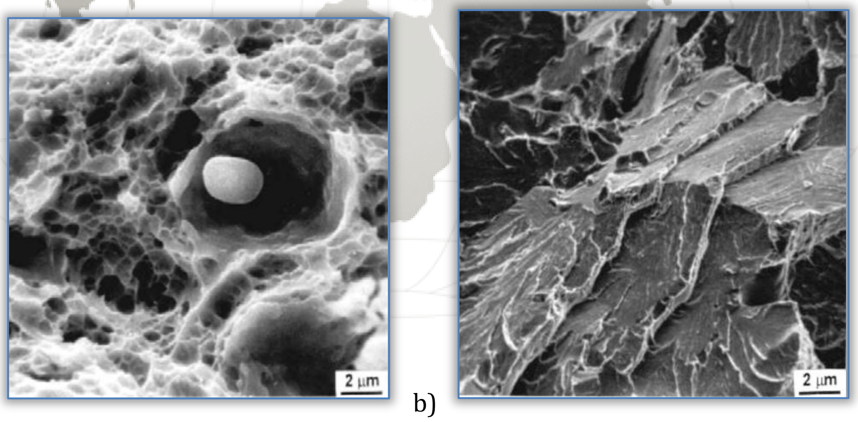
In the introductory part of the paper it was pointed out that the dominant limitation of metal processing with plastic forming, which is particularly evident in terms of the cold bulk processing, is the appearance of cracks or fracture. From the engineering point of view, there are two types of fracture: plastic and brittle fracture (Figure 1). The division is done depending on the level of plastic strain (accumulated energy) to which the material is subjected to before the damage.



a) b)

Figure 1.Types of fractures in metallic materials a) plastic shaped glasses and cone, b) brittle [9]

The appearance of broken surfaces in plastic and brittle fracture of steel with 0.4% C is shown in Figure 2. In morphological terms, the surface of plastic fracture contains large and small pits (created in the oxide non-metallic inclusions and carbide sediments), while on the surface of brittle fracture there are changes in cleavage plane on the subgrain limits with characteristic "river patterns" [10].



a) b)

Figure 2. The appearance of broken surfaces - steel 0.4% C: a) ductile crack; b) brittle crack, (SEM)[10]

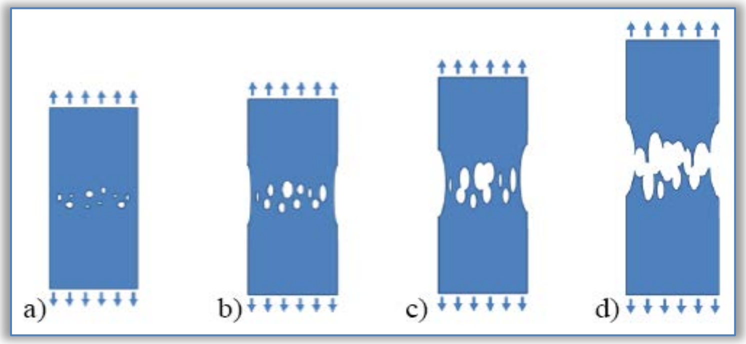


Figure 3. Schematic representation of phase of tensile plastic fracture:
a) nucleation, b) the growth, c) coalescence, d) destruction of materials[11]

Plastic fracturetends to occur at higher amounts of strain and is characterized by relatively slow destruction of metal with considerable accumulation of energy. The emergence and development of plastic fracture in the process of tension is carried out through the following phases, which are schematically shown in Figure 3:

- nucleation (generating) of microcavities,
- the growth of microcavities,

- interconnection (coalescence) of microcavities, and
- fracture (destruction) of materials.

It is known that in the process of super plastic forming of extremely pure materials the fracture can occur preceded by an extremely high value of plastic strain. However, for now only plastic fracture is considered the main reason for unsuccessful processing in conventional processes of bulk forming. Moreover, it should be noted that in the metal forming there are cases where plastic fracture is a projected part of the technological process of processing (e.g. Spark forming).

3. NUCLEATION OF MICROCAVITIES

In principle, commercial materials and alloys contain more hard and brittle secondary phases, which oppose the smooth running of a forming process. Microvoids are generated in areas around hardly formability particles as a result of a high strain level of the metal base. If the material contains only one type of secondary phases, at some point, under unfavorable constellation of stress-strain relations nucleation of microvoids can occur. With the increase of external load in the process of forming, strain strengthening of material and generation of higher tensile values takes place on the boundary surfaces of crystal grains of the metal base and secondary phases. When the strain reaches a critical value, border areas are separated, and there is a fracture of particles. The influence of the type and volume of particles of secondary phases on the plasticity of steel material in tension is shown in Figure 4.

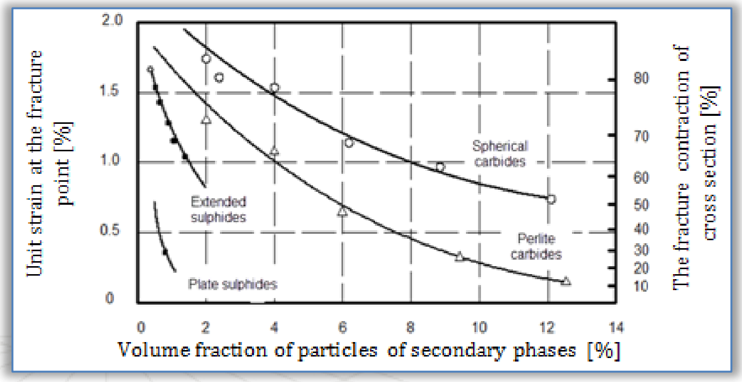


Figure 4.The impact of the volume fracture of particles of secondary phases on plastic properties of steel in tension [12]

In the initial phases of development of plastic fracture, nucleation of microcavities takes place continuously, but not the same time in all secondary phases. First microvoids are mainly generated by larger particles (usually on a non-metallic inclusions) and with increasing the level of strain they grow, with simultaneous nucleation process in the smaller particles. The process becomes even more complicated for materials which contain several types of secondary phases. The mechanism of nucleation of microvoids in steel materials can be different [4-7]. One of the often present mechanisms is decohesion, the occurrence of microvoids at the interface between the second phase and the metal base. The microvoids occur as a result of various possibilities of strain of soft base and hard particles of secondary phases. In general,decohesion may be present in border areas between the grains of the metal base.

The size of the critical strain, at which the process of nucleation of microvoids begins to unfold with mechanism of decohesion, is influenced by several factors [13]: content, size, shape and orientation of the particles of the secondary phase, particle strength, strength of metal base, generated stress state on border surface, strength of border surface, achieved level of strain, the ratio of hydrostatic and effective stress, processing temperature, deformation speed, and so on. According to literature data, to different theoretical approaches are used to define the critical level of deformation in which the secondary particles lose their connection with the metal base.

On the basis of energy criteria, nucleation of microvoids on the border surface between the secondary phase particles and metal base can happen when local concentration of accumulated elastic energy becomes equal to the amount of energy needed to create a new surface. However, this condition is not sufficient, because it does not take into account the effects of local plastic deformation. Strain criterion is based on the assumption that the greatest influence on the formation of microvoids decohesion is exerted by the increasing level of strain, causing intense accumulation of dislocations near the border surface. According to stress criteria, beginning of decohesion primarily depends on the size of surface stress at the border surfaces, i.e. on the strength of the border surface. The stress-strain criterion assumes that large stresses and large strain are necessary for the process of nucleation with mechanism of decohesion. This in practical terms means that a high dislocation density is not a sufficient condition for the creation of microvoids, but shear stresses are necessary in order to move dislocation loops to the border surface. Regardless of the possibilities offered by the above criteria, in micromechanical modeling of nucleation microvoids with mechanism of decohesion it is assumed that the particles of the

secondary phase are deformed only elastically, and metal base plastically [14]. Another mechanism of nucleation of microvoids in the process of forming is fracture of secondary particles. Previous studies have shown that in terms of cold forming the start of fracture depends on the shape, size and brittleness of particles, but predominantly on the level of strain. The main impact of brittle particles in the generating and development of microstructural damage is manifested by the change of the local stress state, in the zone of its immediate surroundings. Size of stress concentration primarily depends on the form of secondary particles. In doing so, the smallest effect is manifested by spherical particles. However, for other types of particles, stress concentration is intense and not only present on the border surface, but extends to a metal base. Therefore, the dimensions of the microvoids which are generated by fracture mechanism of lamellar particles are higher than the dimensions of microvoids resulting from the fracture of globular particles. To describe the fracture mechanism of secondary particles two modelsare used: fiber load model and dislocation model [13]. Regardless of different theoretical approaches, both models are formulated on the assumption that local stress increase due to forming of the metal base with sliding mechanism is necessary forthe development of microvoids in the particles.
According to Benzerga [15], there are key parameters that affect the nucleation of microvoids. Their effect is, depending on the dominant mechanism, represented in Table 1.

Table 1. The impact of key parameters on the mechanism of nucleation of microvoids[15]

Parameter	Trend of influence	
	Decohesion	Fracture
Flow stress of metal base	-	+
The coefficient of deformation reinforcement of metal base	-	+
Elongation of particles of secondary phase	-	+
The strength of particles of secondary phase	+	+
Axial load	-	+
Transverse load	+	-
The ratio of hydrostatic and effective stress(σ_H / σ_e)	+	-

Typical examples of nucleation of microcavities nucleation with decohesion mechanisms and fracture of the secondary particles are shown in Figure 5. At the same time mechanisms of decohesion and fracture are shown in Figure 6.

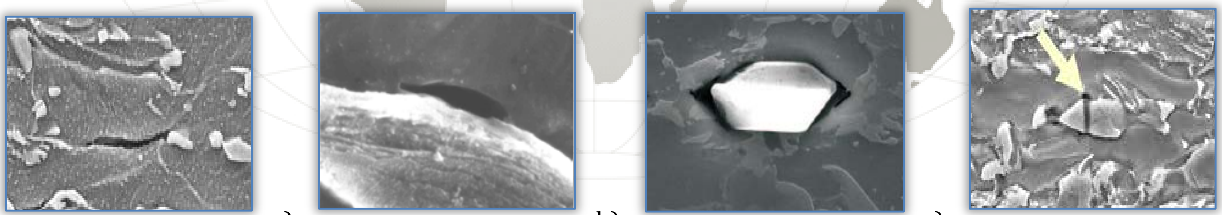


Figure 5. Mechanisms of microcavities nucleation: a) decohesion on the border area of ferrite grain [5], b) decohesion and creating of microcavities at the border area of martensite / ferrite[6], c) decohesion on border area of dual phase steel and aluminum-oxide inclusions [16], d) nucleation of microcavities with mechanism of fracturing martensite particles [4]

Figure 6. Nucleation of microcavities of with mechanism of decohesion and fracture [16]

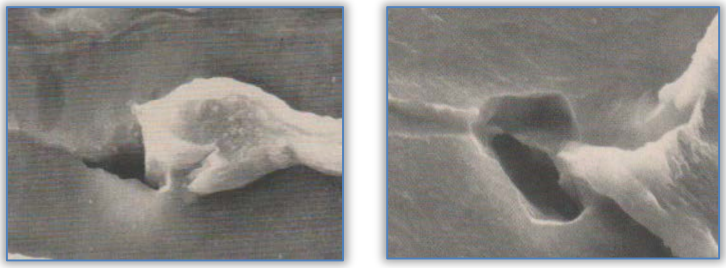


Figure 7. Nucleation and growth of microcavities at place tripartite merger between the two ferrite grains and martensite [6]

In addition to the mechanism of nucleation due to decohesion or fracture of secondary particles, microstructure damage in the process of deformation can occur in other ways. Sidjanin and Miyasato [6] observed that the nucleation of microcavities in tension happen in places of tripartite merger of border area between the two ferrite grains and martensite – Figure 7.
Microcavities can be generated in places of tripartite merger of crystal grains of the metal base (e.g. where three ferrite grains are connected), but it mainly happens only at higher level of strain [7].

4. GROWTH OF MICROCAVITIES

The growth of microvoids phase is closely related to the presence of hydrostatic stress because the intensity of growth greatly depends on the character of the effect of certain components of the stress (domination of compressive or tensile stress) in the forming process.

The initial research of this phase of the development of plastic fracture aimed to analyze a microvoid in the infinite part of the plastic material. It was found that the intensity (speed) of growth of cylindrical (McClintock) and spherical shape cavities (Rice and Trasey) depends on the realized stress-strain state and coefficient of strain hardening [13, 17]. Therefore, the material damage caused by coalescence of microvoids will be promoted only in high ratio of hydrostatic and effective stress. Further research of Rice and Trasey is concerned with the analysis of the impact of strain hardening in the process of growth of microvoids. The results showed that the increase in strain hardening requires a higher ratio $\sigma H / \sigma ef$, if a constant value of growth rate of microvoids should be retained. Rice and Trasey's microvoids growth model is based on the analysis of a single microvoid and does not take into account the possibility of their mutual interaction, and does not foresee eventual damage to the material.

The best known constitutive model to describe the growth of microvoids in material damage when tightening has been proposed by Gurson [14]. He defined a criterion of approximate growth of cavities in porous materials with a rigid perfectly plastic material base. The model has been further improved by Tvergaard, who studied strain and damage in the development of a series of cylindrical microvoids based on a simulation using finite element method, taking into account the strain strengthening in the matrix material [18]. A typical example of the growth of microvoids in the tension process is shown in Figure 8. SEM results were obtained during the research of the impact on the distribution of martensite microstructure in the development of damage to the two-phase ferritic-martensitic steel [4].

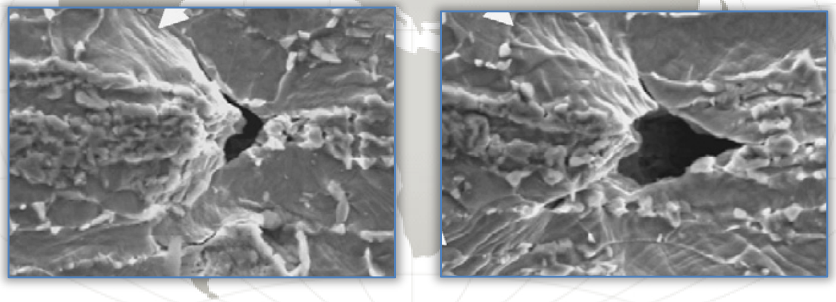


Figure 8. The growth of microvoids in tension of dual phase ferritic-martensitic steel [4]

In paper [2] more information was announced concerning different theoretical approaches used in defining criteria of plastic fracture which are based on models of microvoid growth.

COALESCENCE OF MICROCAVITIES

The final phase of development of plastic fracture is characterized by the intense coalescence of microvoids (Figure 9). With the less plastic materials the process of connecting of microvoids begins immediately after their nucleation. However, if the material has a certain potential of deformability the coalescence will take place in the microvoids, which previously increased significantly.

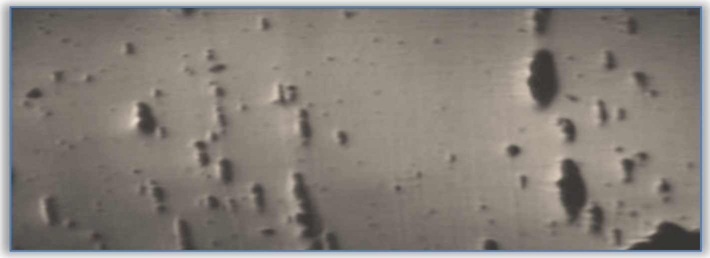
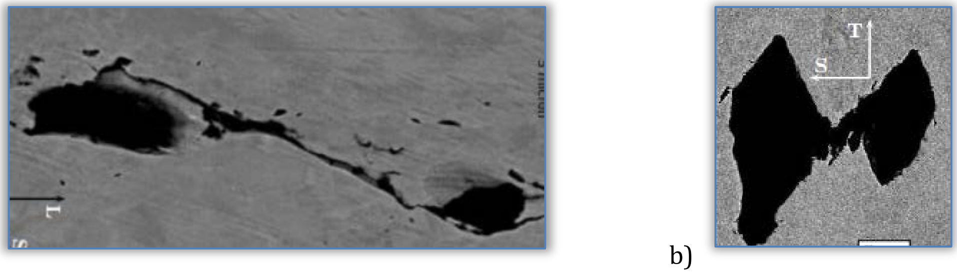


Figure 9. Connecting cavities in the area of sample fracture in tension [19]

The most important and most commonly used criterion of coalescence of microvoids has been suggested by Tvergaard and Needleman. Basically, it is a modification of the Gurson's model, according to which the coalescence of cavities occurs at a critical value of cavity fraction. In doing so, the effects of nucleation of new and growth of existing cavities are taken into account. Benzegra [15] proposed a micromechanical model of coalescence of cavities based on microstructural parameters such as the size of the ligament between the cavities, and the shape and distribution of cavities. The model can successfully predict the acceleration factor of coalescence and critical volume fraction of cavities in Tvergaard - Needleman's criteria.

According to [15], coalescence of microvoids can be done in two ways, depending on several parameters, with the character of generated stress state effect having the strongest impact (Figure 10).



a) b)

Figure 10. Coalescence of microvoids: a) fracture ofthe ligaments due to shear instability, a) fracture of the ligament due to reduction in cross-section[15]

Forming processes that are implemented when compressive stress prevails are characterized by the occurrence of coalescence due to tearing ligaments between microvoids due to shear instability - Figure 10a. On the other hand, due to the effect of tensile stress, coalescence occurs gradually, as a result of reduction in cross-section of ligaments between the microvoids, which have previously increased substantially - Figure 10b.

THE EFFECT OF STRESS STATE ON THE OCCURRENCE AND DEVELOPMENT OF PLASTIC FRACTURE - "STRESS TRIAXIALITY" CONCEPT

The previous analysis of phases of plastic fracture indicates that the generated stress state activates certain mechanisms of microvoids nucleation, where the start and intensity of microstructure damage are directly affected by the character of external load. For the same level of plastic strain, the level of damage to the constituents of microstructure is larger under the influence of tension in comparison to the compressive stress state. Therefore, in the scientific and technical literature the effect of stress state on the development of damage to the material is studied by using the so-called "stress triaxiality" concept, which basically constitutes dependency of the effective strain at the point of fracture formation) on the ratio between hydrostatic and effective stress $\eta = \sigma_H / \sigma_e$:

$$\varphi_e^g = f\left(\eta = \frac{\sigma_H}{\sigma_e}\right) = f\left(\frac{\frac{\sigma_1+\sigma_2+\sigma_3}{3}}{\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}}\right) \quad (1)$$

where σ_i, i=1-3 are the main components of normal stress.

This approach enables to present the character of stress state and to take into account its impact on the emergence and development of plastic fracture.

In the past, a number of studies have been published that have focused on this issue (e.g. Atkins [20], Brünig [21-22], Li [23], Barsoum [17]). The results of experimental - numerical research have shown that in addition to increasing the level of strain, the ratio σ_H / σ_e plays a key role in the formation of fracture in the plastic material. Variation in η factor is mostly achieved through tensile tests, where real or virtual models of samples were used with different geometrical configurations of the reference part.

In paper [24] it was pointed out that Bao and Wierzbicki also extensively studied the impact of character of stress state on plastic fracture. Perhaps the most important result of their work is the criterion that graphically interprets the dependence of effective strain in the fracture φ_e^g on the ratio $\eta = \sigma_H/\sigma_e$ – Figure 11. According to Bao – Wierzbicki criterion, the critical level of accumulation of microstructure damage occurs when effective deformation reaches an amount that is greater than the limit values shown in Figure 11.

However, it is obvious that this phenomenon affects the conditions in which forming process takes place. In fact, depending on the value of "stress triaxility" factor η, which, among other things, affects the activation of specific mechanisms of coalescence of microvoids in the process of deformation two morphologically different types of plastic fracture can occur.

If such a state of stress is generated in the material where factor $\eta < 0$, the coalescence of microvoids takes place with mechanisms of tearing ligaments due to shear instability. Macroscopic damage to metal components that arise in these circumstances are known as "shear" pitting fractures. But, if $\eta > 1/3$, then damage is generated as a consequence of nucleation of microvoids, wherein the growth and finally coalescence occur due to decrease in their mutual distances. In this case "level" pitting fracture arises. In the transition area $0 < \eta < 1/3$ simultaneous action is characteristic of both coalescence mechanisms. It is experimentally confirmed that the value of $\eta = -1/3$ is the lower limit below which hydrostatic power has no effect on the value of strain at the fracture point. Barsoum and co. [17] have, through extensive studies of this issue, confirmed the influence of "stress triaxility" factors on the occurrence of plastic fracture.

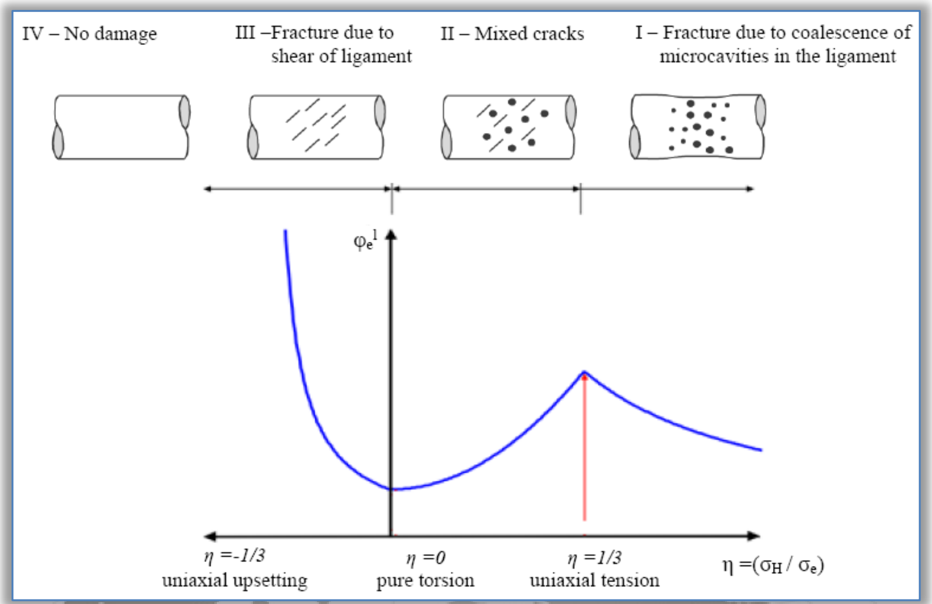
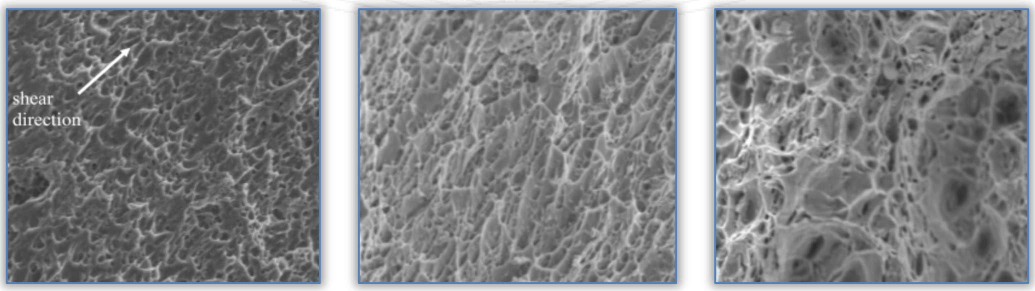


Figure 11. Graphical representation of Bao – Wierzbicki criterion – dependence of the effective strain at the fracture point on ratio (σ_H / σ_e)[24]

By changing the stress conditions from low to high values of η factors, using SEM microscopy, the effect of different mechanisms coalescence of microvoids was identified (Figure 12), which affected the morphology of fracture surfaces. The appearance of the fracture surface, which was formed at low values of η factor is characterized by small shallow pits (the average value of less than 5 microns, [17]), whose elongation orientation is in the direction of shear (Figure 12a). This is due to the impact of the stress state, which did not allow high growth of microvoids before their coalescence. Figure 2.15c reveals a completely different mechanism of plastic fracture. There are great deep pits on the fractured surface. They occurred as a result of significant growth of generated microvoids, which was fueled by high values of η factors. Some of the microvoids before coalescence reached value up to 15 microns, [17].



a) η =0,47 b) η =0,85 c) η =1,10

Figure 12. The appearance of broken surfaces in high-strength steel: a) low value of η factors, b) the transition area, c) high value of η factors[17]

But, Barsoum and co. claim that it is more reliable to predict the initiation and development of plastic fracture through a parameter that characterizes deviation stress state (Lode parameter). This especially refers to the processes of forming in which low values of "stress triaxility" factor are present. Explicit influence of stress state on the value of forming limit, as numerical indicators of material formability, has been experimentally verified in many published studies. The results presented in [25] show that when testing samples made from low carbon steel about eight times higher value of the effective strain limit is obtained under the conditions of uniaxial compression than when the same samples were deformed by uniaxial tension. A typical example of the influence of stress state on the possibility of forming has been presented in the paper by Kampuš and et al.[26]. The results of experimental studies indicate an increase in formability of the material in the process of deep drawing with a reduced wall thickness, by an additional force which compresses the workpiece rim during processing. Also, the results show that the strain limit can increase up to 40% in this way. The paper further points out the possibility of obtaining pieces with flat rim, which is not typical in the processing of the same parts without intensified compressive effect. Extensive research results on the impact of stress state on the limit design possibilities in the process of cold bulk metal forming were presented in the publication by Vujović [27].

CONCLUSION

Initial microstructural state is a very important factor in the formability of the material, because the distribution, orientation, shape and proportion of particles of secondary phases have a dominant influence on the nucleation and growth of microvoids. But, the forming process is equally important because the creation of an adequate processing system can affect the generation of the stress-strain state that will slow the development of damage in microstructure and propagation of plastic fracture. Thus, an integral approach when studying possibilities of limit forming, based on multidisciplinarity, represents a promising solution for optimal and rational design of technological processes in cold bulk processing.

Acknowledgment

This paper and investigation has been realized as part of Tempus WIMBNo. 543898project implementation, a project co-funded by the European Union.

Note

This paper is based on the paper presented at The VIth International Conference Industrial Engineering and Environmental Protection 2016 – IIZS 2016, organized by University of Novi Sad, Technical Faculty "Mihajlo Pupin" Zrenjanin, in Zrenjanin, SERBIA, October 13–14, 2016

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