Journal of Theoretical and Applied Mechanics, Sofia, 2012, vol. 42, No. 3, pp. 61–74

MECHANICAL BEHAVIOUR OF CONVENTIONAL MATERIALS AT EXPERIMENTAL CONDITIONS OF DEEP DRAWING TECHNOLOGICAL PROCESS

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[Received 20 March 2012. Accepted 14 May 2012]

Abstract. The paper deals with experimental investigations on the mechanical behaviour of body-centred-cubic (BCC) and face-centred-cubic (FCC)-conventionally structured sheet metalic-metalic materials under stress-strain conditions of a deep drawing process determined by a coefficient close to the limiting one for Steel 08 and punch diameter of 50 mm. The mechanical characteristics of the investigated materials are identified by one-dimensional tension tests. The materials' responses, as results of identical loading conditions, are described by the change of blank sizes and characteristics of the forming processes. The chosen deformation path ensures obtaining a qualitative steel piece and leads to failures of aluminium and brass blanks.

The reported results could be useful for investigations and predictions of the mechanical responses of such type metallic structures applying microscopic instrumented observations and numerical simulations.

Key words: deep drawing experiments, transversal anisotropy.

1. Introduction

Sheet metal plastic forming is a method of obtaining pieces having small thickness. The high productivity is ensured by the capability of material to be deformed through maximum ratio without failure. On a macro-level, that is determined by the material characteristics and interactions in the material's structure on micro- and mezzo-levels, as well as a given configuration of the produced pieces.

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In general case, many of the recent conventional materials possessing metal structure are built from single crystals or polycrystals according to the solid state physics [1, 2]. In these structures, the character of plastic flow is determined by the interactions between the dislocations. They are few kinds of displacements: inside of crystal lattice, together with the crystal lattice and with available obstacles met inside of the lattice. It is well known, the movement of dislocations in the lattice or through an obstacle needs a surmounting of energetic barrier by combinations from applied stresses and thermodynamic activation. In this way, the mechanical behaviour on the macrolevel is determined by the mechanisms acting on the lower levels. They include mechanisms related to the movement of dislocations and their multiplication, statistics of the movable dislocation populations, nature and statistics of the distribution of obstacles and relations between strain rate applied exteriorly and dislocation kinetics [3].

The three main types of crystal lattice configurations: body-centred-cubic (BCC), face-centred-cubic (FCC) and hexagonal-closed-packed (HCP) play a crucial role on the thermal activation effect in the mechanical behaviour of relatively pure metals. Each one in between the three metallic structures determines the thermo-mechanical behaviour related to the existing sliding systems, symmetry and kind of dislocation nature.

The flow stresses at BCC-metals depend strongly on the strain rate and temperature, while at FCC-metals the flow stresses generally are provoked by strain hardening. In other words, that shows that the crossing of the dislocations is the main mechanism defining the behaviour of FCC-metals during plastic deformation. The surmounting of Peierls-Nabarro barrier is a main mechanism for the BCC metals [3, 4].

The present paper deals with experimental investigations on the mechanical behaviour of few conventional sheet metals during deep drawing. These are steel and brass having body-centred-cubic (BCC) crystal structures and aluminium having face-centred-cubic (FCC). The aim of elaboration is to identify experimentally the mechanical responses of the three materials under one and the same deformation path. For this reason, the blank geometries are chosen to be the same. This choice is not conformed to the limiting drawing ratios, permissible by the three materials. Its main goal is to put the three different materials' structures in one and the same blank volumes, to subject these volumes under one and the same complex forming stress-strain state and finally to observe experimentally the material's-materials' responses. Another aim is to read experimentally some important characteristics of this sheet metal forming process as diagrams "drawing force–punch travel", crucial points on them, displacements of blank flange contour, nature of blank forming and failures *etc.*, which could be considered as very important milestones in the efforts to research the deep drawing by numerical simulations.

Two processes are simultaneously developed during forming by deep drawing in the volumes occupied by the blank materials [5, 6]. One of them is the process of plastic strain development [7, 8]. The other is the process of blank form change [9] according to the form given in advance by the forming tool. The stability loss of plastic strain development leads to plastic strain localization, necking and blank breaking [10]. The stability loss of plastic forming leads to wrinkles on blank surface [11]. The stability loss of any one in between both the processes compromises the production. On this basis, a third aim of present investigations is to observe the development of both the processes in the pointed out metals depending on the normal anisotropy.

The influence of crystal lattice structure in a plastic flow condition could be taken into account according to [5, 12] by the equation:

$$\bar{\sigma} = \left\{ \frac{1}{1+K} \left[K \left| \sigma_1 - \sigma_2 \right|^a + \left| \sigma_1 \right|^a + \left| \sigma_2 \right|^a \right] \right\}^{\frac{1}{a}}, \tag{1.1}$$

where σ_i $(i = 1, 2)$ are the main stresses, $a = 6$ for BCC-metals, $a = 8 - 10$ for FCC-metals, and K is coefficient of transversal (normal) anisotropy. The values of a are based on the crystallographical calculations. This flow condition could be transformed in the Hill's condition (1948) with corresponding values for a and K. Looking at the equation (1.1), the conclusion follows that the increasing influence of crystal structure leads to the decreasing influence of transversal anisotropy. In this sense, the weight influence of both factors transversal anisotropy and crystal structure represent a special interest during a real metal forming and definitely under limiting conditions. These numbered facts provoke the need of formulation and the conduction of the following examinations. The one-dimensional tension tests and deep drawing experiments carried out in this elaboration could be contributable to the tracing and the evaluating the roles of the above two factors proposing actual values and blank forms upon the actual deforming paths.

2. Experimental base

The deep drawing process is very dynamical in production. In difference from the production conditions, the experimental conditions give an opportunity of relaxation of the quasistatic forming load by the material struc-

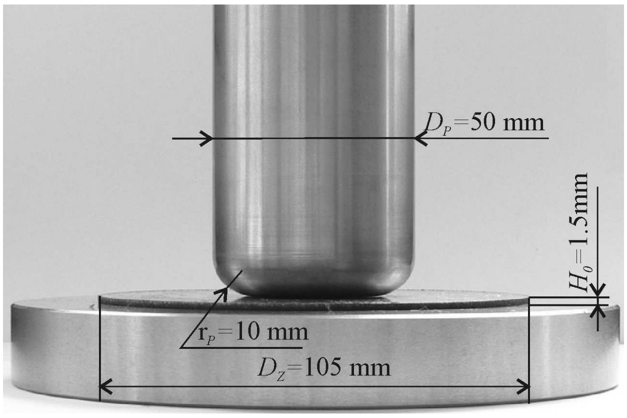

Fig. 1. Forming equipment

tures at decreasing the strain rate influence. Another advantage of the chosen experimental method is the opportunity of long time observation.

A series of deep drawing experiments of rotational axis-symmetrical pieces having inside diameter of $D_D = 50$ mm (equal to the punch diameter of $D_p = 50$ mm in Fig. 1), thickness $h = 1.5$ mm and inside bottom roundness $r_D = r_p = 10$ mm is carried out. The blank given in Fig. 1 has diameter of $D_Z = 105$ mm and thickness of $H_0 = 1.5$ mm. The blank materials are cut from steel 08, aluminium and brass. In order to repeat the results, series of experiments are carried out with each material using the forming equipment shown in Fig. 1. The blank holder specific pressure is adjustable on the range of $q_0 = 1 \div 2$ MPa. Machine oil is used for lubrication. The friction coefficient is $\mu = 0.1$ [13]. The die roundness radius is manufactured as an optimal one $r_m = 11.74$ mm for steel [14], in order to observe maximum materials' effects. This optimal value is computed under equal weigh influence of both the drawing force and punch travel upon the optimal values of the die and punch roundness radii and hole between them. Also, the blank diameter is chosen to be $D_Z =$ 105 mm in order to achieve deep drawing coefficient $K_d = D_p/D_Z = 0.476$ near to the limiting one for a conventional material as Steel 08 for example, usually used in deep drawing [8, 9, 13]. That gives an opportunity to compare different materials' responses at one full consumption of the plastic potential and at blank failures.

The tension tests and deep drawing experiments are accomplished by universal test machine ZD 10/90 equipped with an automatic writer. The deformation velocity is a constant. It assures constant strain rates close to zero and quasi-static deformation conditions, respectively. The tension force and the material displacement are measured during tension experiments. The deep drawing force and the work punch travel are measured during deep drawing experiments. Three experiments are carried out with each of the materials in order to achieve a repetition of the results.

It is well known, that the deep drawing process is realized in two deformation stages and in three geometrical stages [15, 16]. At the first deformation stage, the development of plastic flow is concentrated in a free ring area determined by both the roundness radii of the punch and of the die [15]. This stage is characterized by a plastic transformation of the pointed out area from ring to cone, and during this time the blank flange contour does not move. That means there is no plastic flow in the blank flange. The second deformation stage begins in the beginning of the blank flange movement. The plastic flow spreads in the blank flange.

The three geometrical stages of the deep drawing are related to the punch movement which causes the blank form change [16]. During the first geometrical stage, the blank material is covering the die and the punch roundness radii. The pointed out stage continues until positioning of both the roundness centres in a horizontal line. After this stage, the punch movement forms a blank wall during second geometrical stage. During that, the material of flange is moved and transformed in a blank wall. Third stage begins when the blank flange contour moves on the die roundness radius. During these three stages, the investigated materials pass through one and the same forming paths in which the variable complex stress-strain states begin with one-axial pressure in the flange and finish with two-dimensional tension in the bottom. The actual values of process parameters and effects obtained as results of the material behaviour during above process stages will be discussed in the next section.

3. Experimental results and discussion

The transversal (normal) anisotropy of materials possesses a special significance during the production of pieces by deep drawing process [7, 8, 10]. Its low value causes breaking effect. The plain anisotropy caused by rolling during the metal sheets production leads to different sizes of pieces following the blank flange contour. At first, during the deformation the stability of the blank form change must be ensured in order to produce a given piece. So, on macro-level, for each material the stress-strain dependencies are determined by series experiments and the coefficients of transversal anisotropy K are calculated. The obtained hardening curves are presented in Fig. 2 for the tested three materials. The tests are carried out with constant velocity of machine $V_M =$

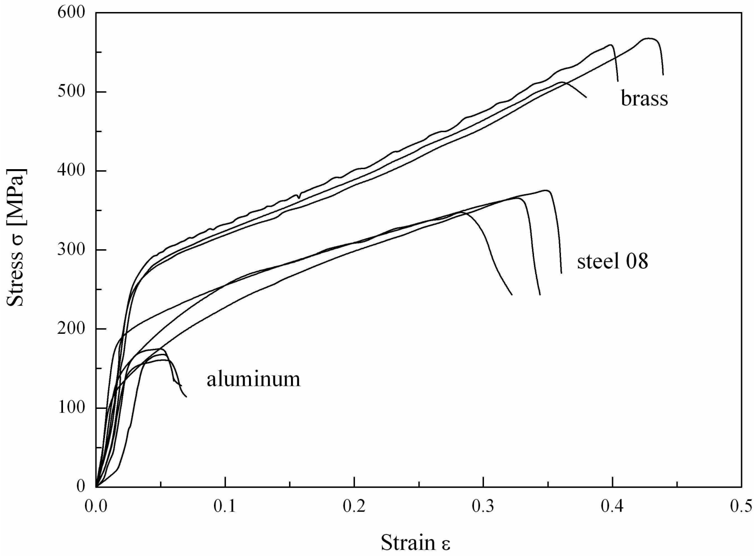

Fig. 2. Experimentally obtained stress-strain diagram of the investigated steel, aluminium and brass

0.07 mm/sec ensuring quasistatic strain rate $\dot{\varepsilon} = (5.81 \div 6.94) \times 10^{-4}\,\mathrm{sec}^{-1}$ (quasistatic deformation conditions). The removal of the dynamical factor on the one hand, and a properly designed forming tool on the other, preventing the part of bending stresses induced by die roundness in the complex stress-strain state, make possible the observations on the ability of the investigated metals to relax the forming loads changing the blank form without failures, as a result of its structural interactions.

3.1. One-axial tension tests

The form and the sizes of the three specimens subjected to one-dimensional tension are in accordance with the EN ISO No 6892 – 1:2009. They are bands with lengths 150 mm and cross sections 5×1.5 mm^2.

The type of tension failures is shown in Fig. 3(a), (b), (c) for the steel, aluminium and brass, respectively. Analyzing the Figs 2 and 3, the conclusion can be drawn that the investigated specimens could be classified as perfect–plastic body (Fig. 3(b)), elastic-plastic body possessing mean hardening (Fig. 3(a)) and elastic-plastic body possessing huge hardening (Fig. 3(c)). Their behaviour will be observed during deep drawing. The transversal anisotropy of the three specimens is calculated according to [6]:

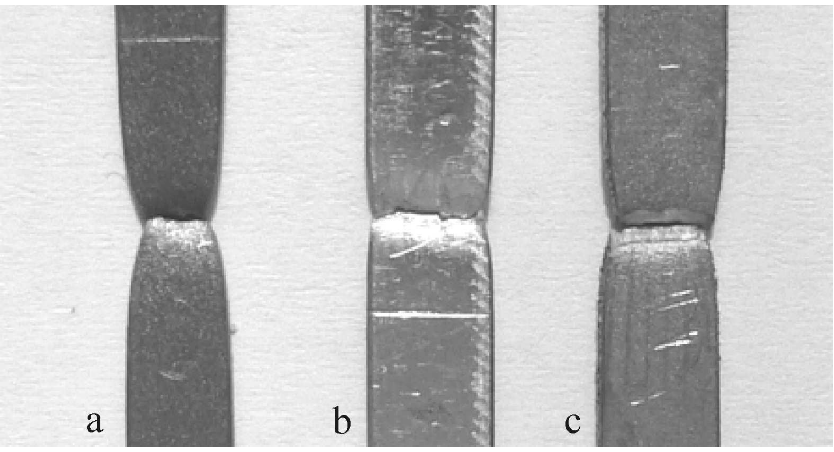

Fig. 3. The type of tension failures for (a) steel; (b) aluminium; (c) brass

$$K = \frac{\ln\left(\dfrac{w_o}{w_f}\right)}{\ln\left(\dfrac{h_o}{h_f}\right)}, \tag{3.1}$$

where w denotes the width and h denotes the specimen thickness; the subscripts o and f denote the initial and final specimen sizes. The transversal anisotropy is evaluated as follows: for the steel $K_{\mathrm{St}} = 1.7$, aluminium $K_{\mathrm{Al}} = 0.53$ and brass $K_{\mathrm{Br}} = 0.88$. The following conclusions could be made looking at the Fig. 3 and equation (3.1). The different transversal anisotropies are a reason for the different kinds of failure seen in Fig. 3. A strong thinning along the width is observed for the steel specimen (Fig. 3(a)), while the thinning along the thickness is slow. That effect permits a better relaxation of the forming loads during cold plastic deformation by deep drawing. The broken cross section of the Steel 08 specimen is 2.1×0.2 mm^2. A small width thinning of the aluminium sample is observed in Fig. 3(b). The reason is the low coefficient of transversal anisotropy. It leads to a decreasing deep drawing ability with increasing deforming ratios. The broken cross section of the aluminium specimen is 3.45×0.4 mm^2. The brass shown in Fig. 3(c) possesses mean transversal anisotropy looking at the form and the values. Its broken cross section is 2.95×0.6 mm^2. That supposes corresponding effects during deep drawing tests. The next experiments of deep drawing are accomplished after the one-axial tension tests, revealing the above mechanical behaviour of tested blank materials.

3.2. Experiments of deep drawing

The results of deep drawing experiments are shown in Fig. 4. The specimens shown after the end of the forming process are: steel in Fig. 4(a); aluminium in Fig. 4(b, c); brass in Fig. 4(d, e). The experimentally obtained diagrams "Drawing Force P – Punch Travel S" are shown in Fig. 5.

Figure 4(a) reveals that the process of deep drawing of Steel-steel 08 blank having above mentioned sizes can be successfully performed without breaking of the material. The piece obtained with limit forming rate possesses inside diameter of $D_D = 50$ mm and high of $h_D = 45$ mm. The "P–S"-diagram obtained during forming is shown in Fig. 5, and denoted by letter a. The maximal drawing force is $P^{St} = 8.9 \times 10^4$ N obtained with work punch travel $S^{\mathrm{St08}} = 28.8$ mm [17]. Visually, it is seen evaluating the obtained pieces that the BCC-structured steel 08 combined with the other material structure characteristics [1] supports better the forming loads, preventing the loss of stability of both the processes of form change and strain development [5–11] during the whole deep drawing process. The blanks with the same sizes, but made of aluminium and brass are broken with punch travels $S^{\mathrm{Al}} = 12.8$ mm and $S^{\mathrm{Br}} = 28$ mm, respectively. The difference between the two kinds of failures is seen in Fig. 4(b) and (d). The corresponded "P–S"-diagrams are denoted in Fig. 5 by letters b and d, also. The aluminium blank is broken plastically by diffusive necking. A small crack is formed, and it increases with increasing punch travel while the drawing force decreases. The blank breaks slowly and noiselessly. That shows the aluminium materials' structures dissipate deformation energy. In the case of the brass blank, a brittle breaking is observed. The crack is formed by a sharp tearing as a hit, which shows an accumulation and discharge of deformation energy by the brass structures.

The tendency of aluminium to ductile breaking could be remarked in Fig. 4(c). An arrow shows the place of the plastic strain localization. The shown form of the blank is obtained with punch travel $S^{\mathrm{Al}} = 11.84$ mm and drawing force $P^{\mathrm{Al}} = 1.52 \times 10^4$ N (Fig. 5, curve c). The blank has variable contour on the range of 101.05 to 102.9 mm. A square form is observed as a result of plain anisotropy. The blank height is $H^{\mathrm{Al}} = 13.1$ mm. The blank thickness along the periphery of flange is not changed $h^{\mathrm{Al}} = 1.5$ mm. A comparison between Figs 4(c) and 3(b) gives a reason to comment the type of failure as a typical one for the FCC-metallic materials. In such a material, the flow stresses are generally provoked by the strain hardening which is a

Fig. 4. Pieces obtained of deep drawing experiments: (a) Steel 08; (b, c) aluminium; (d, e) brass

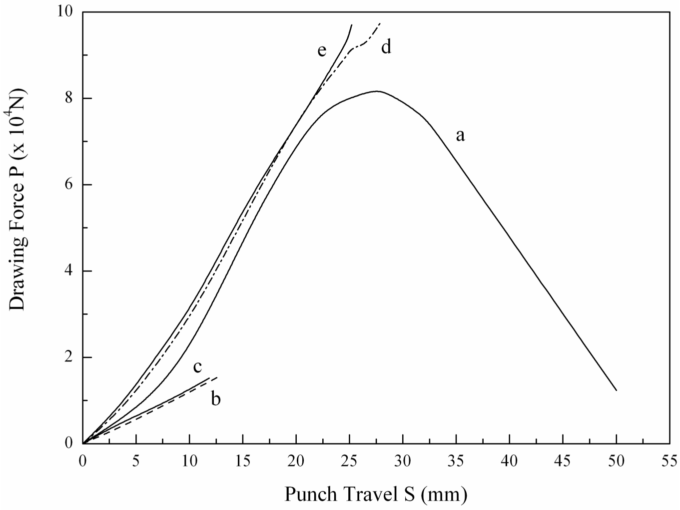

Fig. 5. Experimental diagrams "Drawing force P – Punch travel S": (a) Steel 08; (b, c) aluminium; (d, e) brass

consequence of the cutting off dislocation forests cutting. It is seen in Fig. 2, that aluminium does not possess sufficient strain hardening i.e. there is a lack of obstacles able to stop the movement of dislocations. As results, higher forming loads are not supportable and corresponding change of the blank form is not happening. Instead, a small width tinning of specimen is seen in Fig. 3. It shows the deformation until breaking is at expense of thickness decrease.

An increase of the punch travel from $S^{\mathrm{Al}} = 11.84$ (Fig. 5, curve c) to 12.8 mm (Fig. 5, curve b) yields an increasing drawing force $P^{\mathrm{Al}} = 1.56 \times 10^4$ N, necking and blank crack given in Figs 4(b, c). The blank contour diameter is in limits of 100.0 to 102.15 mm depending on the plain anisotropy. The contour displacement of 1.075 mm shows that there is a small developed plastic flow in the flange, and the basic part of deformation energy is concentrated in the FCC structures of cone area between the die and punch roundness radii. Here, the plastic flow is determined by the strain hardening ability of the pointed out area.

The above commented local necking and crack growing do not appear during the brass blanks failure shown in Fig. 4(d, e). Firstly, that suggests that the examined material accumulates elastic deformation energy. Secondly, this energy could not be relaxed because of the lack of proper plastic deformation mechanisms and that breaks the blank through a massive crack curtly formed. The corresponding “P–S”–diagrams are denoted by letters d and e in Fig. 5. In contrast to aluminium, the punch travel is two time larger at the brass blank, in Fig. 4(d), $S^{\mathrm{Br}} = 25.3$ mm (Fig. 5, curve e). A stability loss of form change occurs in the blank flange before the failure. The blank contour is on the range of 91.7 to 92.65 mm which shows lower plain anisotropy. The contour movement is from 6.65 to 6.175 mm. The blank height is of $H^{\mathrm{Br}} = 26.05$ mm. The thickness along the blank flange contour changes from $h^{\mathrm{Br}} = 1.5$ to 1.6 mm. That indicates a presence of plastic flow in the blank flange, and material’s ability to support the forming load by an increasing blank flange thickness. The waves formed on the flange have height of $w_Z = 3.3$ mm. An increase of punch travel to $S^{\mathrm{Br}} = 28.0$ mm breaks the blank with drawing force $P^{\mathrm{Br}} = 9.8 \times 10^4$ N (Fig. 5, curve d). The contour is on the range of 90.65 - 91.55 mm. The above commented tendencies are kept. The actual blank height is $H^{\mathrm{Br}} = 29.0$ mm. The actual blank thickness is $h^{\mathrm{Br}} = 1.65$ mm.

After above analyses and comparing the blanks shown in Figs 4(a–e), the conclusion is evidential in between the investigated materials the steel’s structure is more capable to be processed by cold plastic deformation under conditions of deep drawing than the structures of investigated aluminium and brass.

A comparison is performed between the Figs 4(b, c) and 4(d, e), as well as, Fig. 5(curve b, curve c) and Fig. 5(curve d, curve e), and the values obtained for the punch travels, blank heights, blank contour displacements *etc.* That leads to the conclusions that both the failures of aluminium and brass blanks happen at different stages of the forming process. That means under different stress-strain states of blanks. As already was mentioned above, at the end of first deformation stage and the beginning of the second one, plastic flow in the blank flange is initiated. Before this effect, the free blank area between the punch and the die is deformed under tension, pressure and bending on the die roundness radius. The failure of aluminium blank shows an inability of plastic deformation mechanisms to keep the material's continuity in such a treated blank volume. That results in impossibility of blank wall formation. The blank is broken soon after beginning of the second deformation stage and during first geometrical stage. The wall formation in the brass and the steel blanks demonstrates a successful passing of the two materials through these stages. The brass blank is broken immediately after beginning of the second geometrical stage and under conditions of second deforming stage started according to the sizes of the die and punch roundness radii and blank thickness after $S = r_m + r_p + h_0 = 11.74 + 10 + 1.5 = 23.24$ mm. Then the blank wall forming is begun. The part of blank material covered the punch roundness radius is already undergone the plastic deformation. The elastic strains remain only in this part. The function of this blank part during the second geometrical stage is to transfer the drawing load from the punch face through the blank bottom, the formed wall and to the blank flange periphery. The blank flange is subjected to a complex stress state with predominant pressure as a result of the contour displacement approximately in 7 mm. That causes the flange waviness. The flange is hardened as a consequence of the deformation mechanisms acting in the investigated brass. Together with that, the necessary drawing force increases, and it must be transferred by the wall to the flange. In this way, the blank wall is subjected to one-axial tension which breaks the blank. The crack sharply propagates in the area connecting the bottom roundness and the wall.

It is seen from the reported experimental results and their analysis, that in the case of aluminium blank, from both the processes developed in the blank volume firstly the process of plastic deformation looses the stability and a diffuse necking nucleates, followed by crack. In the case of brass blank, the loss of stability of flange forming firstly appears with the process development under a larger punch travel, which leads to increasing tangentional pressure stresses. This loss can be prevented by an increasing blank-holder force, but that will not ensure a successful finishing of the forming process. This measure will cause a blank breaking with punch travel $S^{Br} = 26.25$ mm and drawing force $P^{\mathrm{Br}} = 9.55 \times 10^4$ N (Fig. 5, similarly to curve d). In fact, that is with 1.75 mm earlier than in the previous case but, also under the conditions of the second geometrical stage under one-axial tension in the wall.

4. Conclusions

The possibilities of deep drawing of a rotational axis symmetrical piece are experimentally investigated in this work. An analysis of the obtained results and observed effects is performed from a point of view materials' responses on micro- and mezzo-levels as a consequence of the interractions between the materials' structures.

It is experimentally observed, that in the investigated aluminium depending on anisotropy 0.53, the cutting of dislocation forests, as a basic deformation mechanism in such type metals, cannot relax the external forming load. That leads to plastic failure of blank during the first geometrical and second deformation stages. The breaking (Fig. 4(b)) is happening with punch travel $S^{\mathrm{Al}} = 12.8$ mm (Fig. 5, curve b) and plastic strain localization, necking, crack forming and slow crack diffusion in the free area between the die and the punch roundness during its transformation from plane to cone.

It is observed: forming of qualitative steel piece without crack (Fig. 4(a), Fig. 5, curve a) through the consumption of full steel plastic potential and failure of brass blank (Fig. 4(d), Fig. 5, curve d) during the experiments with the investigated Steel 08 and brass having transversal anisotropy 1.7 and 0.88, respectively. The brass is broken in a different kind, compared to the aluminium, under conditions of second geometrical and second deformation process stages, when the wall forming begins. In the brass blank, a large crack is sharply formed in the area connecting the wall to the bottom roundness.

The experimentally obtained values of the parameters of forming process could be successfully used in future investigations and predictions of the mechanical responses of similar type metallic structures under complex stress-strain sheet forming states, applying microscopic instrumented observations and numerical simulations.

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