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STRAIN-STRESS CONDITIONS OF SHEAR BAND FORMATION DURING CEC PROCESSING ON A NEW MACHINE WITH CONTROL BACK-PRESSURE

WARUNKI ODKSZTAŁCENIOWO-NAPRĘŻENIOWE TWORZENIA PASM ŚCINANIA W PROCESACH CWS REALIZOWANYCH NA NOWEJ MASZYNIE Z KONTROLOWANYM PRZECIWCIŚNIENIEM

The results of experimental investigations of the CEC processes, performed on a new special hydraulic press with control back-pressure, are presented for the first time. Due this very advantageous conditions of plastic deformation very interesting and unique experimental results, enabling accurate determination of the directions of shear bands formation were obtained. It has been observed that after very large plastic deformation of the solution heat-treated 6082 alloy, taking squares in the presence of high hydrostatic pressure, he the surface of the deformed samples an easily noticed relief is formed, resulting from the formation of numerous intersecting shear bands. It has been found that under conditions of hydrodynamic lubrication, all shear bands are formed at the angle of 45° this the extrusion direction and their intersection occurs at the angle of 90°. Such mechanism of shear bands formation allowed determining the true state of strain and stress, occurring in the deformation zone of the CEC processes.

Keywords: cyclic extrusion-compression (CEC); severe plastic deformations (SPD); strain-stress state; shear bands; aluminium alloys; grain refining

W niniejszej pracy po raz pierwszy przedstawiono wyniki badań eksperymentalnych procesów cyklicznego wyciskania (CWS) przeprowadzonych na nowej, specjalnej prasie hydraulicznej z kontrolowanym przeciwciśnieniem. Dzięki zapewnieniu bardzo korzystnych warunków odkształcania plastycznego uzyskano interesujące i unikalne wyniki badań eksperymentalnych, pozwalające na wyraźne ujawnienie kierunków tworzenia pasm ścinania. Mianowicie stwierdzono, że po bardzo dużych odkształceniach plastycznych przesyconego stopu 6082, realizowanych w obecności wysokiego ciśnienia hydrostatycznego, na powierzchni odkształconych próbek powstaje łatwo zauważalny relief pochodzący od tworzenia się licznych, wzajemnie przecinających się pasm ścinania. Stwierdzono, że w przypadku zastosowania bardzo dobrych warunków smarowania narzędzi, wszystkie pasma ścinania tworzą się pod kątem 45° do kierunku wyciskania, a ich wzajemne przecinanie zachodzi pod kątem 90°. Taki mechanizm tworzenia pasm ścinania pozwolił na określenie rzeczywistego stanu odkształcenia i naprężenia, występującego w kotlinie odkształcenia procesów CEC.

1. Introduction

The Cyclic Extrusion Compression (CEC) method, developed and patented in Poland in the year 1979 [1, 2], is widely used in the investigations of microstructure and mechanical properties evolution under severe plastic deformation (SPD) conditions. The other main SPD processes are the equal channel angular extrusion (ECAE) [3, 4] and high-pressure torsion (HPT) [5]. A characteristic feature of the three mentioned methods is the possibility of preserving the primary billet geometry at all deformation stages. Another very important characteristic of these methods is the possibility of exerting high hydrostatic pressures, enabling to obtain very large plastic deformation without loss of cohesion of the processed material [6-10]. Using other methods, e.g. the accumulative roll bonding (ARB) [11-13], it is also possible to obtain considerable plastic deformation, however in the case of low plasticity materials, the cracks appear after a few rolling passes, which do not allow to continue the process. Therefore, in some cases, to deform materials of low plasticity, the warm rolling method is used [14]. In the SPD processes, it is possible to obtain very large, even unlimited, plastic strains, however under the conditions that they are performed in the presence of appropriately high hydrostatic pressure.

The initial device for unlimited deformation of metals and alloys by the CEC method is shown in Fig. 1 [2].

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Before the beginning of the deformation process, the billet is subjected to pre-compression by the thrust screws with the F_{c0} force. In this way, the material is deformed cyclically in the presence of hydrostatic pressure $p_h=-\sigma_m$ ($\sigma_m < 0$ – negative mean stress), permitting to achieve high strains without any danger of crack development. The amount of the accumulated true strain is

$$\varphi = 2n_c \ln(S_0/S_m) = 4n_c \ln(d_0/d_m) \qquad (1)$$

where: n_c – number of the deformation cycles, S_0 – cross-sectional area of the chamber, S_m – cross-sectional area of the die orifice, d_0 – chamber diameter, d_m – diameter of the die orifice.

It's necessary to pay attention that local true strains are larger than the strains determined by expression (1). Strains calculated by this expression relate only to material points situated along the symmetry axis. The true strains are larger in these regions, which are more distant from this axis. The increase of true strain results from the presence of additional shear strains. Computer-aided analysis of metal flow by the Finite Element Method (FEM) assures the high accuracy of the evaluation of plastic strains.

Due to hydrostatic pressure, extremely large deformations were achieved, up to φ=90 of the true strain in aluminium [15]. Numerous shear bands and micro-shear bands were found in the microstructure of the aluminium alloys deformed by the CEC method [16-20].

Intensive shearing, occurring in these processes, creates a characteristic chess-board structure, which can be observed even at the magnification of a light microscope, particularly in the case of a coarse-grained billet of Al 99.992 % (Fig. 2a, 2b) [2]. In the shear bands a considerable amount of energy is stored. Therefore, in case of aluminium of high purity, the occurrence of recrystallization has been observed even at room temperature. New grains are usually formed on the boundaries of old grains, especially in places crossed by bands and inside the grains in the areas occupied by bands (Fig. 2b) [21]. The investigations have shown that the development of the microbands is very important in the formation of the nanograin microstructure [22]. It suggests that the studies of strain localization and the development of band microstructure in the deformed materials enable to understand the basis phenomenon of the grain refinement during the SPD deformation.

In order to obtain appropriately high hydrostatic pressure, the billet located in a chamber between two punches is subjected to pre-compression force F_{c0} before the process is started. In the course of turning the screws, intended for pre-compression of the billet, the device's frame undergoes tensile elastic deformation. Therefore, the tensile stresses occur also in the frame, which enable to store suitably large pre-compression force F_{c0} (Figs. 1, 3). When the process is started, the stored pre-compression force F_{c0} becomes the counterforce F_c. However, under the influence of additional elastic extension of the frame by the process forces F_e, a disadvantageous decrease in the counterforce takes place immediately after the beginning of the process, i.e. $F_c < F_{c0}$ (Fig. 3). For this reason it is necessary to apply appropriately greater pre-compression force F_{c0}. The counterforce F_c should guarantee complete filling of the tool space behind the die in all performed deformation cycles and at the same time ensure sufficiently high hydrostatic pressure within the deformation zone. When the punches are moving, the friction forces in front of the die decrease, while behind the die increase. However, the increase in the friction forces behind the die is possible only in the case of complete filling of the tool space. If the applied counterforce F_c does not guarantee sufficient filling of the chamber behind the die, the process force F_e becomes reduced, especially at the final stages of the deformation cycle (Fig. 4) [23].

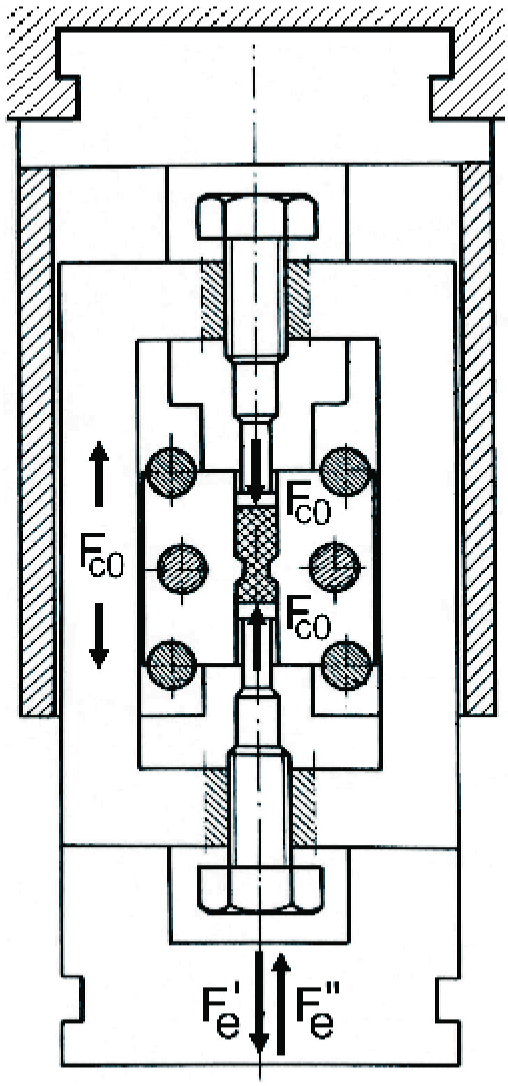

Fig. 1. The initial device for unlimited deformation of metals and alloys by the CEC method with maximal pressing force of 100 kN

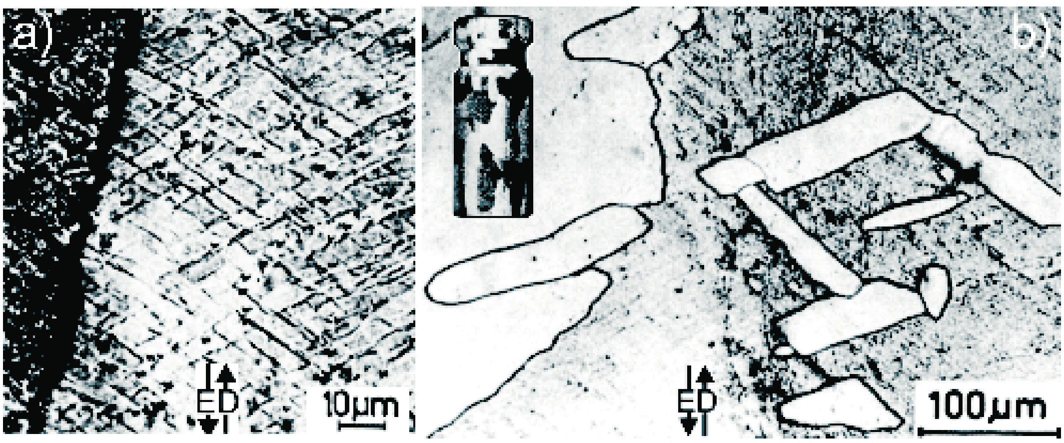

Fig. 2. Chess-board structure revealed in the Al 99.992 grains after 3.6 of true strain – 4 cycles of CEC (a) and colony of new grains after 4.5 of true strain – 5 cycles of CEC (b)

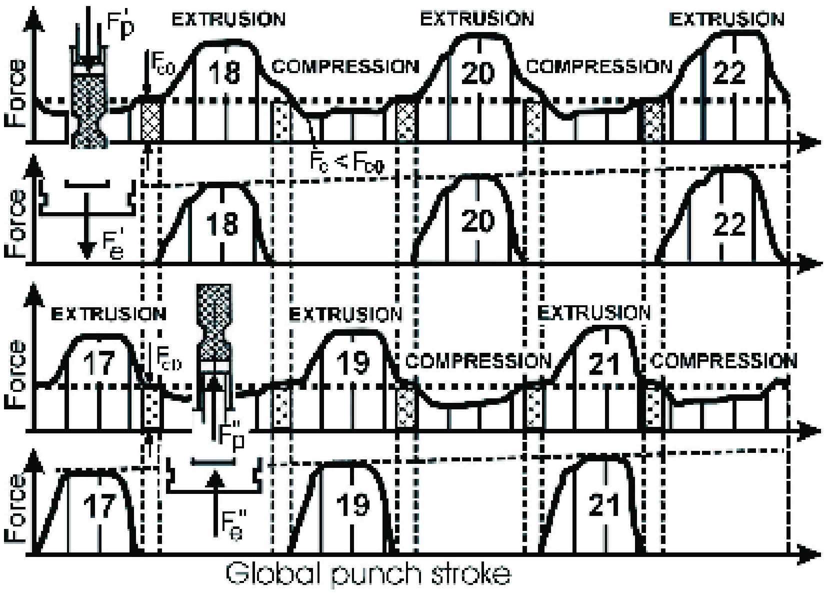

Fig. 3. Fragmentary diagram of forces measured by four special sensors: F_e – forces of the CEC process, F_p – forces exerted by the punches, F_{c0} – pre-compression force

In order to reduce the friction as much as possible it is necessary to use lubricants, which have no tendency to escape from the closed tool space even at very high hydrostatic pressure. For this reasons the most appropriate lubricants are those, which have the consistency of a paste. Their density should correspond to the type of the deformed metal and the applied hydrostatic pressure. In practice, the lubricants can be selected only by means of special preliminary tests of the CEC process.

Recording of the process forces F_e enables a continuous controll of the accuracy of the deformation development (Fig. 4). The process forces F_e measured in the given cycle should not undergo a considerable decrease. The occurrence of a distinct decrease in the process forces F_e is the evidence of an incomplete filling of the tool space behind the die. Such disadvantageous deformation conditions must not occur even during the first cycle. They are the result of applying insufficiently high pre-compression force F_{c0} of the material. If the decrease in the F_e force occurs in the subsequent cycles of the process, it is most often due to the escape of a too thin lubricant from the closed tool space. When the material is pre-compressed by means of screws (Fig. 1), even a smallest outflow of lubricant leads to a considerable reduction of the hydrostatic pressure p_h. In such conditions the material loses its cohesion very quickly, especially behind the die, where deformation of the material takes place through radial extrusion (Fig. 5). At this point, at the absence of hydrostatic pressure ($\sigma_m \geqslant 0$), the plastic deformation of the metal takes place in the presence of tensile circumferential stresses ($\sigma_\theta > 0$).

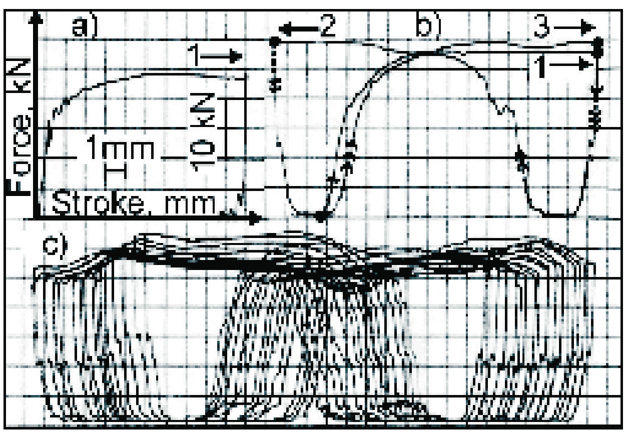

Fig. 4. The forces F_e registered during the CEC processes (99.5 % Al) after 1 cycle (a), 3 cycles (b) and 34 cycles (c)

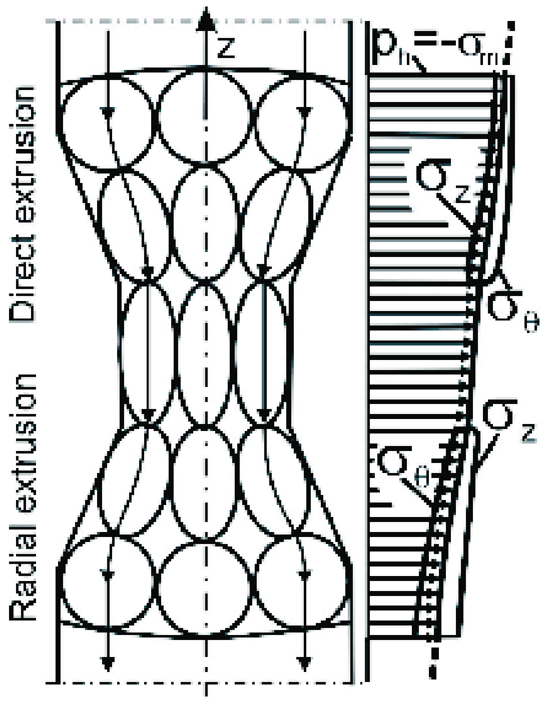

Fig. 5. Distribution of the axial σ_z and circumferential stresses σ_θ, and the hydrostatic pressure p_h along the deformation zone

It should be noted that in spite of the commonly used name of the process: "cyclic extrusion compression – CEC", the plastic deformation realized behind the die, in fact, is not the result of compression but of radial extrusion. In some publications this process is named "reciprocating extrusion" [14, 24]. The real course of the metal flow in the deformation zone is better described by the name: "reciprocating direct-radial extrusion – RDRE" (Fig. 5). However, for the radial extrusion to take place behind the die, it is necessary to use an appropriately large counterforce, i.e. a compressive force directed opposite to the outflow of metal from the die.

The shape of the working surfaces of the die orifice, in particular their inclination in the entrance and exit parts of the die, has the greatest influence on the strain-stress state of the deformed material. As a result of the dual symmetry of the converging die the conditions for metal flow under the direct extrusion conditions first and then under radial extrusion conditions should be similar. Substantial differences may refer only to the sign of the strain components, i.e. to their positive or negative values. For example, if at direct extrusion some strain component is negative, then on the other side of the die, where radial extrusion takes place, the same strain component should have positive value.

It is known from many experimental studies that direct extrusion guarantees advantageous state of stress at arbitrary shape of die also in the case when a flat face die is applied. On the other hand, in the case of radial extrusion only a few shapes of the die guarantee proper conditions of plastic deformation [25, 26].

Increases in the diameter of material extruded radially, when dies with flat surface are used, induce unavoidable cracking or plastic separation of the deformed material as large positive circumferential strains are induced by tensile circumferential stresses. On the basis of theoretical analysis and experimental tests it has been proved that only due to appropriate inclination of the die surface it is possible to guarantee that the deformed material retains its cohesion. It has been found, that the correct deformation conditions are assured by use of dies, which surfaces are inclined at the angle equal to or greater than the inclination of the tangent to the hyperbola L2 (Figs 6, 7). The negative values of average stress, $\sigma_m < 0$, i.e. the hydrostatic pressure, are appearing at such inclination (Fig. 7c). Maintaining of correct deformation conditions was analysed also by means of experimental studies with the application of a die with double inclination of its surface at the angle of 27° and 7°, adjusted to the curve of the hyperbola L2 (Figs 6a, 7c). It has been proved that in such case on the outer surface there appear numerous shear bands, inclined at the angles of 45° to the circumferential stresses (Fig. 8), in which no plastic separation of the outer layer of the extruded sample takes place even at very high true plastic strains, amounting to φ=2.9. Such inclination of the shear bands is in perfect agreement with theoretical predictions (Fig. 9b). It should be assumed that the CEC processes are characterized by similar deformation conditions of the metal, especially behind the die, where metal flow is induced by radial extrusion. The differences may occur only in the values of hydrostatic pressures p_h, which in the case of CEC processes are much higher (Fig. 9). The principal aim of the study is to determine the conditions of shear bands formation in the deformation zone in the CEC process.

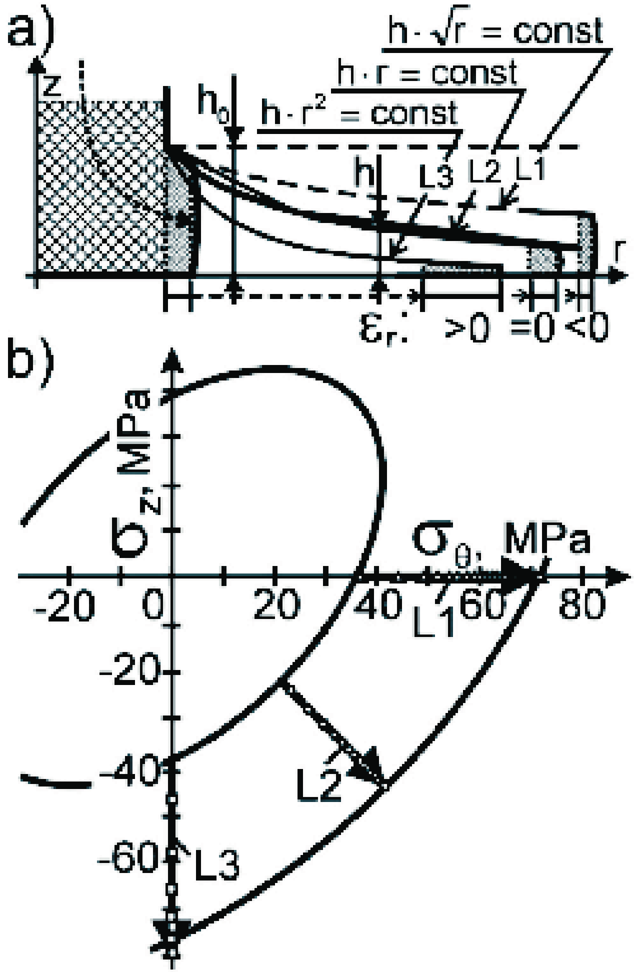

Fig. 6. The influence of die shape on the stress conditions of radial extrusion of aluminium (99.992 % Al): a) the die profiles (L1, L2, L3) forcing the metal flow in under three different stress states, b) the stress paths of the circumferential tension (L1), circumferential-axial shear (L2) and axial compression (L3) [26]

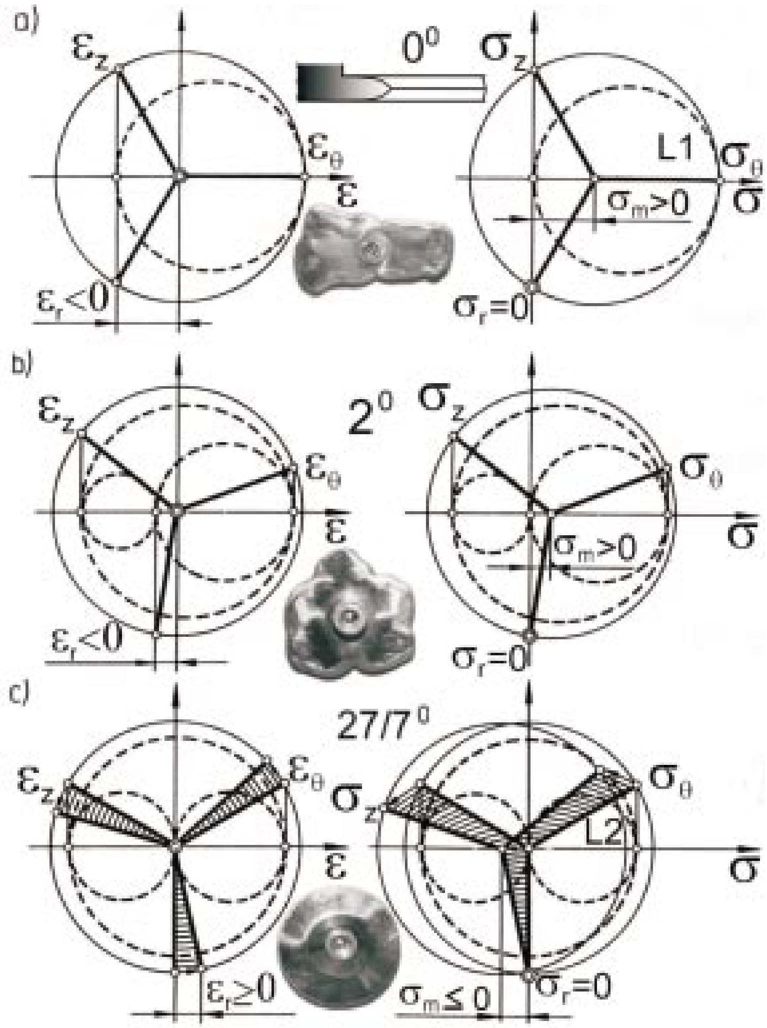

Fig. 7. Graphic representation of the strain-stress states corresponding to the experimental conditions of radial extrusion of aluminium (99.992 % Al) [25]

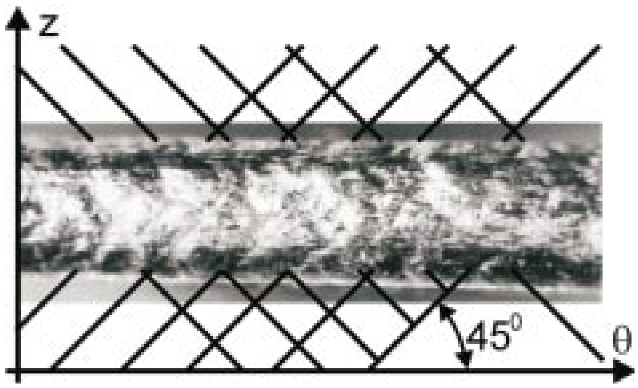

Fig. 8. Shear bands visible on the outer surface of the samples extruded radially [25]

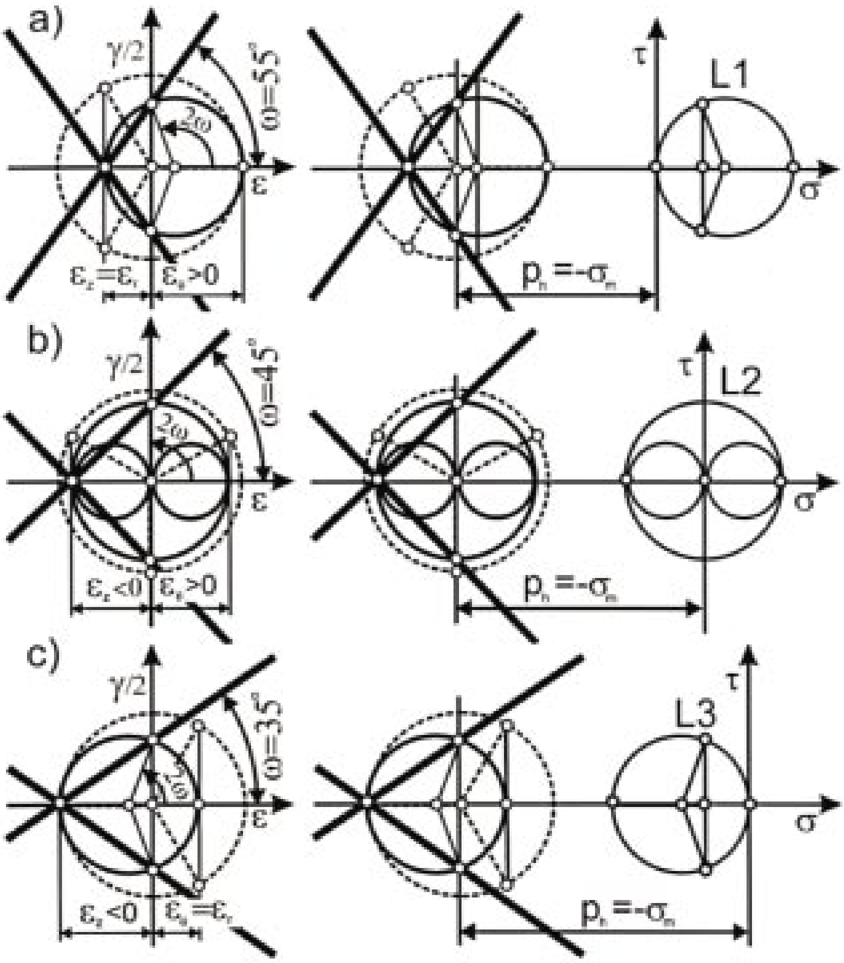

Fig. 9. Graphic representation of the directions of shear band formation during radial extrusion using three different die profiles (L1, L2, L3)

2. Experiment techniques

The unique hydraulic press, having a capacity of 600 kN, was designed and constructed for CEC processing (Fig. 10) [27]. The press is equipped with a microprocessor control system for the CEC processing with intelligent control back-pressure. The microprocessor cooperates with a personal computer, which displays and stores all process parameters.

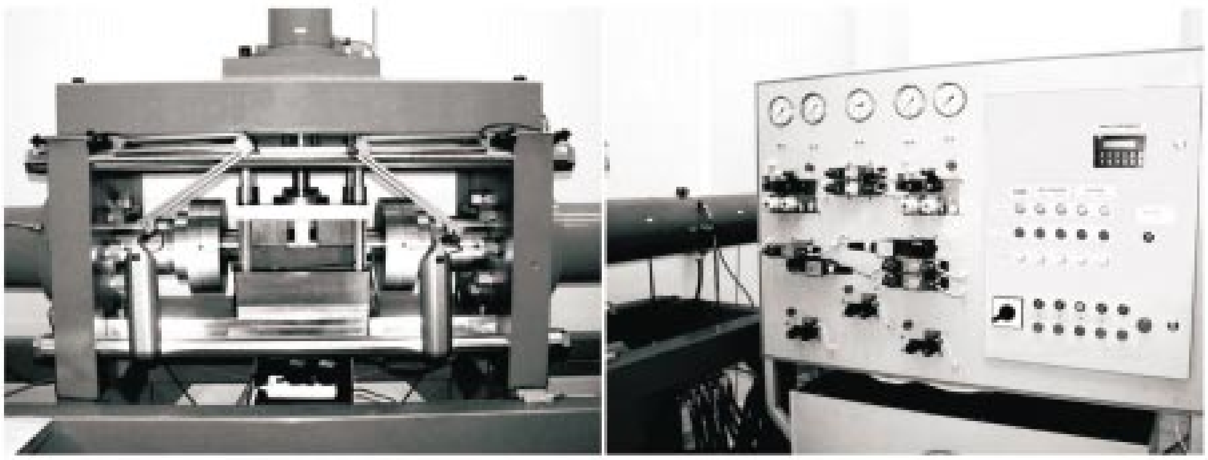

Fig. 10. The CEC press of 600 kN capacity with intelligent control back-pressure

In the experimental studies, conducted on the new CEC machine, the tools, composed of two punches, two chambers and exchangeable dies (Fig. 11) were used. To lubricate the working surfaces of the tools, a dense lubricant prepared from many components, mainly graphite and molybdenum disulfide (MoS_2) was used. To prevent the loss of tightness between the contact surfaces of two chambers and the die, a considerable hold-down force, equal to F_t=140 kN was exerted (Fig. 11a). All CEC processes were performed at very low speed, equal to v=0.1 mm/s, so as to assure the same deformation temperature, close to room temperature.

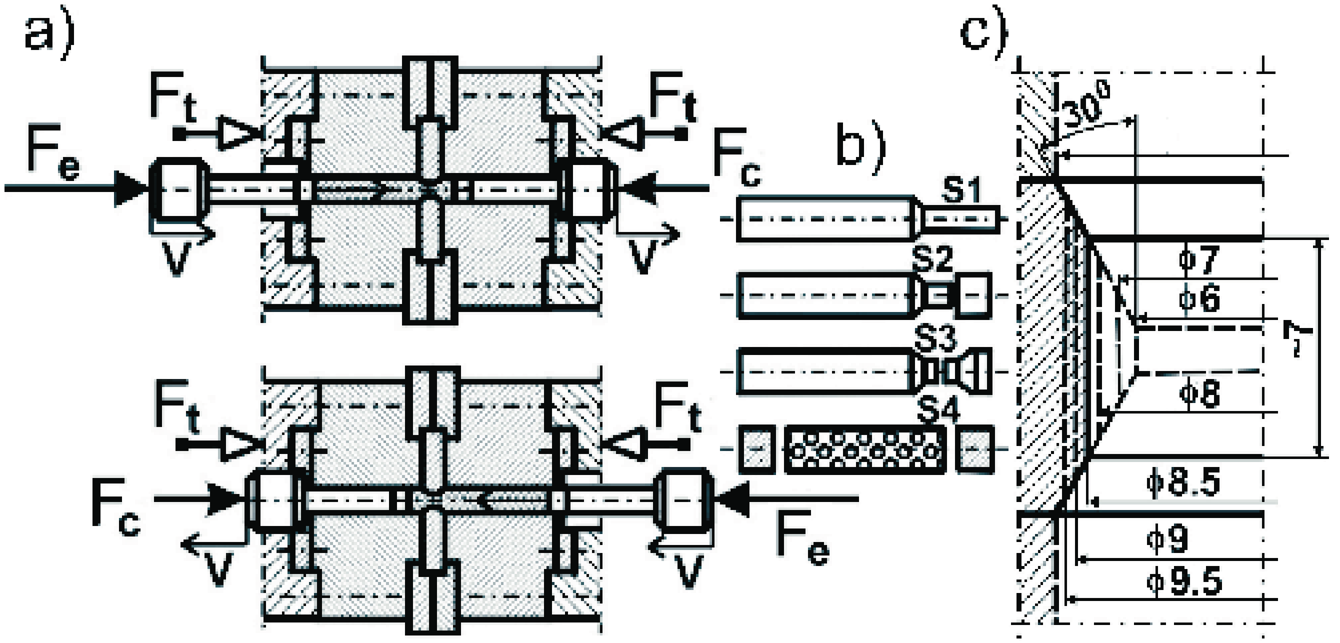

Fig. 11. Operating conditions of the tools during two successive cycles of CEC process: F_e – process force, F_c – counterforce, F_t – force of hold-down tools, v – punch speed (a), the shapes of initial samples (b) and geometry of the dies for CEC processes (c)

Samples of the diameter d_0=10 mm and the length l_0=50 mm, prepared from rods produced in industry by hot extrusion from the 6082 alloy of the chemical composition of Al-1.0Mg-1.18Si-0.66Mn-0.04Cu-0.04Zn-0.03Cr-0.03Ti (in wt.%) were used in the experiment. Immediately before starting the process, the samples were solution heat treated at 525°C for 30 min and then quenched in water. Samples consisting of one part S1, as well as samples consisting of two parts S2 were used (Fig. 11b). The divided configuration of the initial samples (S2, S3) guarantees faster and easier adjustment of the material volume to the working space of the tools at the beginning of the first cycle of deformation. For this reason after the preliminary tests all the next ones were performed using the divided samples S2. Samples of the shape S1 require preliminary compression before starting the first cycle. Samples of three-part divided configuration S4, with two soft-metal ends, can be applied when brittle materials, in particular the powder materials, are processed.

For the CEC processes, performed on the new hydraulic press, the dies with various diameters of the orifice within the range of 6.0-9.5 mm were prepared (Fig. 11c). In all dies, 30° inclinations of the entrance and exit working surfaces of dies were applied. From among many dies prepared for the experimental tests, a die with the orifice diameter d_m=8.5 mm and the length of the die bearing equal to about 7 mm has been selected (Fig. 11c). With the die orifice of such diameter, in accordance with formula (1), in one cycle (n_c=1) the true strain equal to φ_1=0.65 was obtained.

The microprocessor control system of the press enables to operate the CEC processes using the counterforces F_c, selected both manually – by introducing the appropriate value of this parameter to the memory of the microprocessor, as well as automatically – by selecting the appropriate programme of the microprocessor. A standard data acquisition system supported by a PC computer was used to capture and record the process data including the process force F_e resulting from the counter force F_c as well as other process conditions. Additionally, the relationships between forces F_e and F_c were plotted on the computer screen as a function of time.

The principal aim of the present study is to determine the stress conditions of the shear band formation, since these conditions have the major influence on the possibility for obtaining high plastic deformations and the nanocrystalline structure of the processed material. From among many realized tests, for the description of the results, connected with this problem, there have been selected only three processes, characterized by completely different conditions for selection of hydrostatic pressure in the deformation zone. Three selected processes allow clear and concise presentation of the analysed problems.

3. Investigation results

Favourable conditions for deformation by the CEC method are obtained when the possibly smallest counterforce F_c is applied, which however guarantees such hydrostatic pressure within the deformation zone that enables to preserve the cohesion of the processed material in all cycles of the process. Due to the application of the possibly smallest counterforce F_c, it is possible to obtain the required high plastic deformation with minimal forces F_e of the process, preventing quick damage of the tools. Selection of the appropriate counterforce without the aid of a suitable computer programme is a difficult task.

Correct choice of hydrostatic pressure in the first cycle is very important (Fig. 12, Table 1), since already at the beginning of the process when the material is not yet work hardened, the tool space must be completely filled with the deformed metal. At low back-pressure the chamber situated behind the die is not completely filled, and the conditions of radial extrusion in the presence of tensile circumferential stresses become very disadvantageous. During such deformation, the hydrostatic pressure does not occur since the values of the mean stress behind the die are greater than zero, i.e. $\sigma_m > 0$. When the metal is being displaced behind the die it does not adhere completely to the walls of the chamber. In such a case the process force F_e is mainly determined by the deformation conditions existing in front of the die, and not behind it. In front of the die, with the reduction of the length of the extruded metal, the friction forces at the chamber wall become always smaller. However, these friction forces, at low counterforce, are not balanced by appropriate increases in the friction forces behind the die. In such a case the process forces F_e become smaller, which is evidence that the CEC process is carried out in highly inappropriate stress conditions, resulting from too small counterforce F_c.

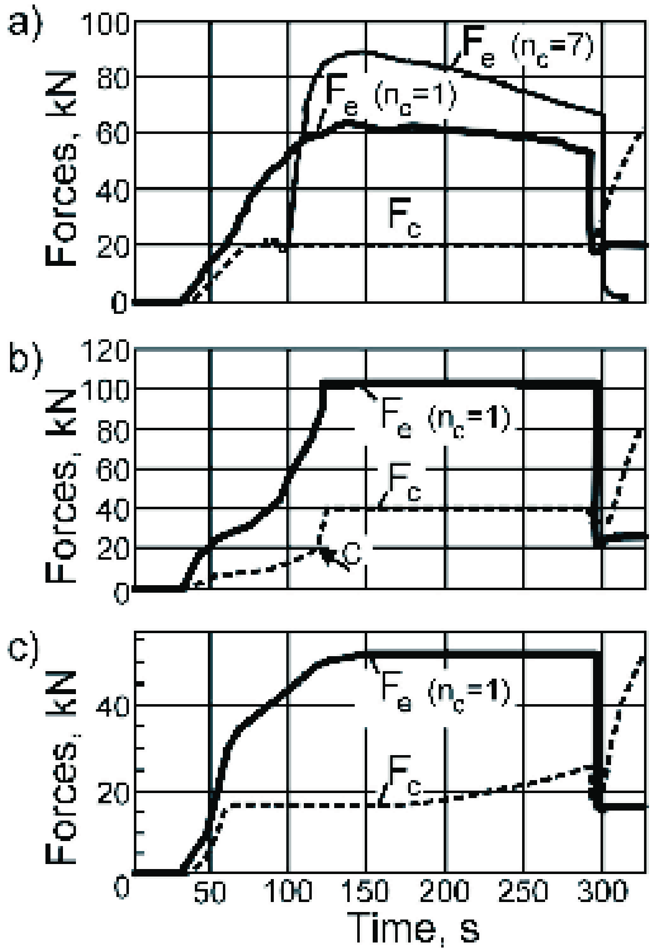

Fig. 12. The forces of CEC processes occurring with the use of different counterforce: a) too small, b) excessively large, c) optimum

On the basis of the graphs, recorded by computer, it has been noticed that the application of the counterforce F_c=20 kN leads to a considerable decrease in the process forces F_e, already during the first cycle (Fig.12a, Table 1). It has been also noticed that with increasing work hardening of 6082 alloy this decrease becomes greater, and in the last cycle (n_c=7) it was very distinct. After removing the deformed sample from the chambers, numerous shear cracks could be observed on the surfaces of the processed 6082 alloy (Fig. 13a). It has been found that these cracks are inclined at an angle of 45° to the extrusion direction. The counterforce of 20 kN is too small and the hydrostatic pressure within the deformation zone is also too low to prevent cracking. Cracks appear in the areas of the largest accumulation of plastic deformations, i.e. within the shear bands. For this reason, cracks have been formed at 45° angle to the extrusion direction.

TABLE 1

Results of experimental tests

Test number	Cycle number True strain	Counterforce Back-pressure	Extrusion force Extrusion pressure	Method of selecting the counterforce (evaluation of the back-pressure values)	Evaluation of preserving the cohesion; quality of obtained alloy
	n_c φ	F_c p_c	F_e p_e		
1	7 4.6	20 kN 255 MPa	62-52 kN 790-660 MPa	Manually (to low back-pressure)	Incorrect; cracks, (Fig. 13a)
2	9 5.9	40 kN 510 MPa	105 kN 1340 MPa	Manually (too high back-pressure)	Correct; no cracks (Fig. 13b)
3	15 9.8	18-26 kN 229-331 MPa	52.5 kN 668 MPa	Self-acting (optimal back-pressure)	Correct; no cracks (Fig. 13c)

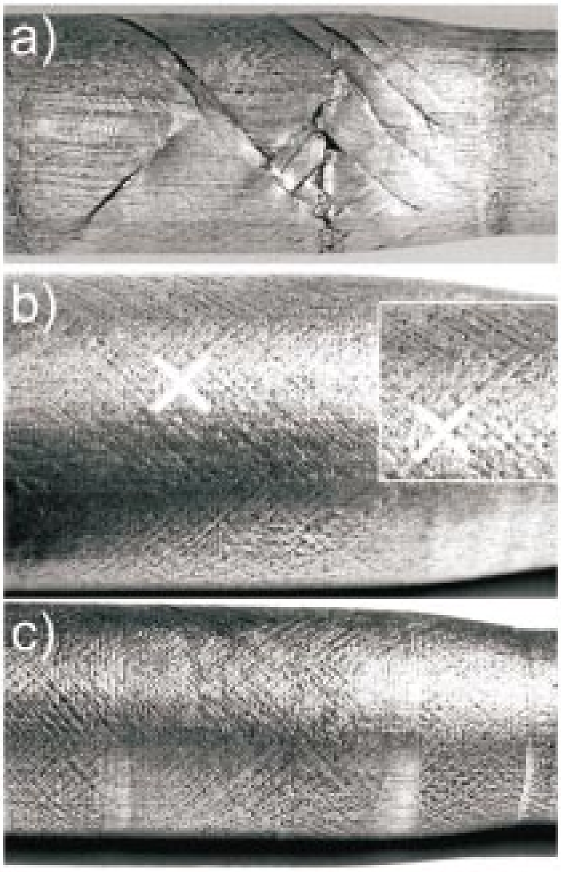

Fig. 13. Cracks and surface traces of shear bands exhibited by the 6082 alloy CEC processed using different back-pressures: a) too low, b) excessively high, c) optimum

It has been concluded from the above that in order to retain cohesion of the 6082 alloy, the counterforce must be increased. Since the value of a sufficient counterforce was not known, it has been decided to carry out a deformation test applying two times greater counterforce, i.e. F_c=40 kN (Fig. 12b, Table 1). It has been found that when applying this counterforce, the process force remains on a constant level, however it reaches an excessively high value, equal to F_c =105 kN. Such great force occurring already in the first cycle creates the danger of the tools damage, especially for the punches. For this reason, after temporary stopping the process, the next cycles were carried out at lower counterforce, equal to F_c=25 kN. In the case of the new hydraulic press, the change of the value of counterforce is easy and quick. The required configuration of the press control parameters is entered to the microprocessor by means of a display panel equipped with appropriate push buttons and a LCD monitor (Fig. 10). The processed sample was taken out of the hydraulic press after carrying out 9 deformation cycles. After removing the lubricant layer it has been found that due to increased back-pressure the cohesion of 6082 alloy has been preserved. However, a much greater and positive surprise was the unexpected look of the outer surface of the deformed sample. On the surface of the deformed sample, a very distinct relief could be observed even without any etching. Its characteristic shape evidences that it was created due to the formation of great many intersecting shear bands (Fig. 13b). From the formed surface relief it can be seen that all the shear bands are inclined at the angle of 45° to the extrusion direction and their intersection at the angle of 90°.

The above way of selecting the counterforce is incidental and it cannot be accepted in practice. For this reason a program has been loaded to the memory of the microprocessor of the hydraulic press, which on the basis of special procedures of complex deduction allows automatically changing of the counterforce and applying its optimal value during the process. First of all, the earlier noticed regularity has been used to elaborate the procedures for determining the required values of counterforce. As observed earlier that the processed material does not lose its cohesion when the process forces in the particular deformation cycles are retained on nearly the same level, i.e. at F_e=const.

The results of starting the first program, guaranteeing automatic selection of the counterforce of the punch are shown on the graph (Fig. 12c). The relatively low value of the initial counterforce equal to F_c= 18 kN was applied deliberately. It is smaller than the value adopted in the first process F_c=20 kN (Fig. 12a). From the results obtained in the second process, it can be concluded that the volume of the processed material is perfectly adjusted to the tool space at the counterforce equal to about 20 kN, which has been indicated by the arrow C (Fig. 12b). When this value is exceeded a rapid increase in the forces (F_c, F_e) takes place, resulting from completion of the adjustment of the material by plastic compression and simultaneous beginning of elastic compression. In the case of microprocessor control system of the deformation process it has been found that after preliminary deformation of an initial sample, in which the volume of the deformed material becomes adjusted to the tool space, limited on both sides by the front surfaces of two working punches, the process force F_e attains the maximal value F_e=52.5 kN (Table 1). It is not very high as it is attained at relatively low counterforce (F_c= 18 kN). It can be noticed that the process force is lower than the maximal force F_e=62 kN, occurring in the first CEC process carried out at the counterforce F_c=20 kN (Table 1). It has been found that in spite of the application of such dangerously low value of the counterforce (F_c= 18 kN), the obtained sample was of excellent quality (Fig.13c) even after 15 deformation cycles.

The positive result of the process was obtained due to the application of the microprocessor control system. The smallest force decrease in relation to the maximal force of the process, occurring at the beginning of each cycle, is immediately revealed by means of appropriate program procedure, and next quickly corrected by proper increases in the counterforce. The greatest increase in the counterforce takes place always at the final stage of each deformation cycle; thanks to it, in the deformation zone situated far from direct action of the counterforce, a suitably high hydrostatic pressure is continuously maintained. It has been found that in the first cycle the counterforce was increased from the value 18 to 26 kN (Fig. 12c, Table 1). In the process the same initial counterforce (F_c= 18 kN) in all deformation cycles was maintained. It has been stated that the graphs of the forces (F_c and F_e) occurring in the particular cycles were similar to the first cycle. Essential differences refer only to the maximal forces of F_e process, occurring in the particular deformation cycles. It has been stated that in each successively realized cycle there takes place a gradual increase in the level of these forces, namely from 52.5 kN (n_c=1) to 88 kN (n_c=15). It has been found that the values of the counterforce F_c, which were selected by means of a microprocessor, did not exceed 30 kN in any of the cycles.

4. Dicussion

The main differences between the stress conditions of CEC processes performed earlier and those performed now are shown on two graphs (Figs 14a, 14b). The arrows OA, overlapping from 7 deformation cycles, show a temporary drop in the pre-compression of the deformed material caused by elastic tension of the device frame at the beginning of each cycle (Fig. 3). Elastic increases in the compressive force (arrows AB), necessary to start plastic deformation of the material by direct extrusion, leads to the increases in the hydrostatic pressure in the deformation zone. At the beginning of the direct extrusion process the highest value of the hydrostatic pressure has been achieved (Fig. 5). While the material particles are displaced along the flow line they are work hardened with a simultaneous decrease in hydrostatic pressure (BC arrows). Due to work hardening, in accordance with the flow criterion, the stress path goes through various yield surfaces. When the material approaches the die bearing, the plastic deformations (CD arrows) are stopped temporarily. While the particles are displaced in this bearing there takes place further drop of the hydrostatic pressure (DE arrows). Behind the die bearing there begins the second stage of deformation in which the initial shape of the particles is renovated by means of radial extrusion (EF-FG-GO arrows). During this deformation path a further decrease in the hydrostatic pressure p_h takes place (Figs 5, 14a).

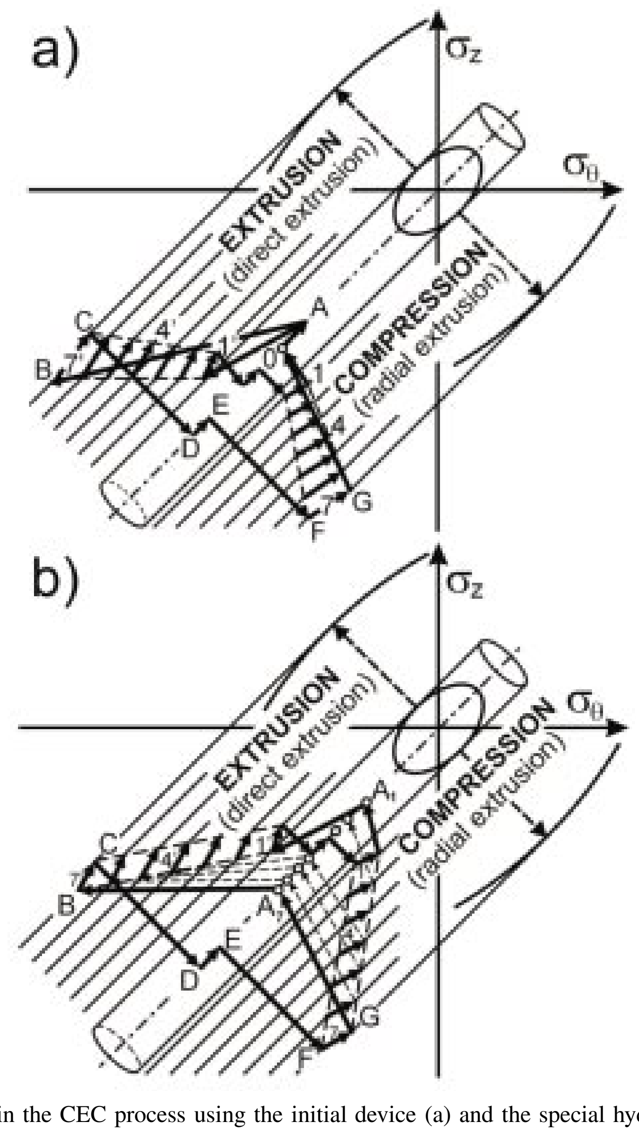

Fig. 14. Evolution of the stress state in the CEC process using the initial device (a) and the special hydraulic press (b)

In the case of application of the special hydraulic press for the CEC processes, the technical possibilities to ensure appropriately high hydrostatic pressure in the deformation zone are more advantageous (Fig. 14b) and the dangerous destressing of the material at the beginning of the process does not occur (OA arrows – Fig. 14a). The CEC processes can be started at the application of low hydrostatic pressures (A_1 – first cycle) and only with increasing work hardening the hydrostatic pressure (A_1-A_7) may be appropriately increased.

The hydrostatic pressure has no influence on the directions of shear bands formation. However, application of low hydrostatic pressures contributes to the increase in deformation inhomogeneity and the occurrence of cracks in the shear bands (Fig. 13a). It has been found that in case of CEC processes performed on the hydraulic press with the application of a die with 30° inclination of the entrance and exit working surfaces (Fig. 11c), all the shear bands are inclined at the angle of 45° to the axis of the processed sample and the intersection of these bands takes place at the angle of 90°. It has been noticed, however, that the actual shape of the conical narrowed area of deformed samples (Fig. 13) does not correspond to the shape of the die. Such effect of the CEC process can be attributed to the fact that in conditions of good lubrication of the material present in the tightly closed interior tool space, there occurs the possibility of optimal, spontaneous configuration of the deformation zone. The processed material chooses then a flow path through the die orifice, which requires the least energy of plastic deformation. In front of the die bearing there are formed stable lubricant wedges, which cause considerable elongation of the conical shape of the deformation zone. As a result the inclination angles of the side surface of the zone are much smaller than that of the die (Fig. 13). Hence it should be assumed that the CEC processes, performed on the new hydraulic press, guarantee the deformation of metal in conditions of hydrodynamic friction, i.e. the most advantageous from among the known types of friction. In such lubrication conditions there does not take place any direct contact between the flowing metal and the tool walls. Accordingly, even in case of quite a number of cycles, amounting to n_c=15, the outer surface of deformed samples retains its original relief, induced by localized strains in the shear bands (Fig. 13c). It can be noticed that in this case the characteristic relief is visible not only on the surface of a cylindrical sample, but also in the area of the deformation zone and the die bearing. This is evidence that even in the die bearing the conditions of hydrodynamic friction are maintained till the end of the process. It should be assumed that such favourable conditions of friction in the die bearing have been maintained due to its rather great length (ca. 7 mm) corresponding approximately to the diameter of the die orifice (Fig. 11c).

It should be noticed that the clear visibility of the localized shearing strains has been obtained due to reversible cyclic deformation, leading to banded location of surface indentations and protrusions, similar to intrusions and extrusions observed in an experimental study of fatigue strength of metals [28, 29]. It should be noticed that there exists an essential difference between the formation mechanisms of the above-mentioned surface relief for non-monotonic loading conditions. In the first case, under the influence of a considerable, cyclic, reversible plastic deformation, a deep, clearly visible surface relief is formed (Fig. 13), corresponding to the directions of shear bands (SB) formation, whereas in the second case, under the influence of small, cyclic elastic-plastic straining, a micro-relief is formed, corresponding to the location of persistent slip bands (PSB) [28, 29].

On the basis of a comparison of the directions of shear band formation, determined theoretically for the particular states of strains and stresses (Fig. 9), with the directions observed experimentally (Fig. 13), a very important final conclusion of the present study can be put forward, namely that in the deformation zone of the CEC processes there occurs a strain state corresponding to axial-circumferential and circumferential-axial simple shear, in which the radial strains assume values equal to zero (ε_r=0), and the circumferential and the axial strains have the same absolute value ($|\varepsilon_\theta| = |\varepsilon_z|$) both in front of and behind the die (Figs 9b, 15). Similar deformation conditions with dominating role of simple shear deformation were presented also in other studies [3, 4, 24].

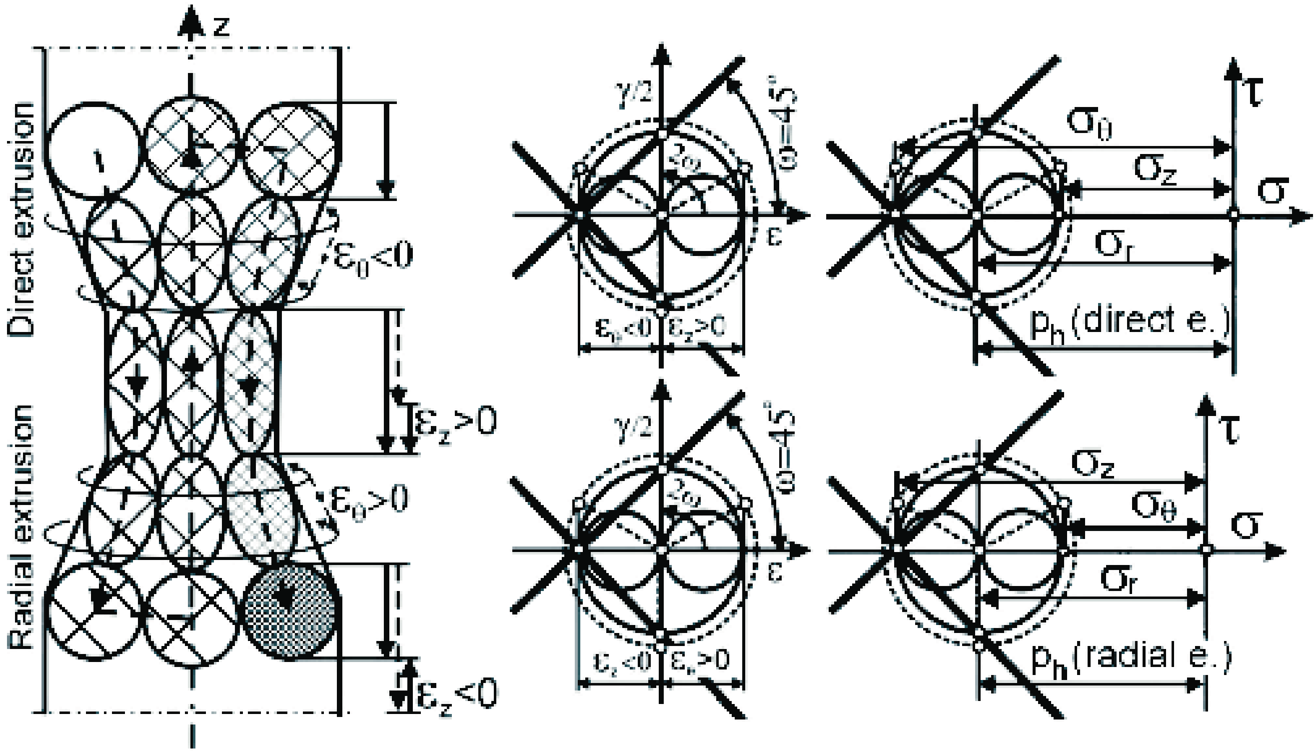

Fig. 15. Graphic representation of the directions of the shear band formation in the deformation zone of CEC processes

The elements of the principal stress tensor and the values of hydrostatic pressures can be determined using the basic theoretical dependences of plastic flow and the numerical data obtained during the performed experimental tests. In the CEC processes the plastic deformations are performed under conditions of multiaxial compression ($\sigma_\theta < 0$, $\sigma_r < 0$, $\sigma_z < 0$). It has been found experimentally that shear bands are formed at the angle of 45° to the principal strain directions. It follows from the above statement that radial stresses take the mean value of the circumferential and the axial stresses (Fig.15)

$$\sigma_r = \frac{1}{2}(\sigma_\theta + \sigma_z) \tag{2}$$

The above value (2) is simultaneously the mean value of three principal stresses

$$\sigma_m = \frac{1}{3}(\sigma_\theta + \sigma_r + \sigma_z) = \frac{1}{2}(\sigma_\theta + \sigma_z) = \sigma_r. \tag{3}$$

Thus the hydrostatic pressure occurring in CEC processes can be defined by the following formula

$$p_h = -\sigma_m = \frac{1}{2}|(\sigma_\theta + \sigma_z)|. \tag{4}$$

The axial stresses σ_z change along the deformation zone (Fig. 5), and behind the die their values depend on the back-pressure p_c resulting from the applied counterforce F_c, while in front of the die they depend on the extrusion pressure p_e resulting from the extrusion forces F_e. The values of all the components of the stress state depend mainly on the flow stress σ_f. To recognize the conditions for the plastic flow of metal in the spatial state of stress, it is necessary to calculate such equivalent stress σ_v, which can be compared with uniaxial stress. In the forming technology the distortion energy hypothesis (Mises and Huber) is used for this purpose. According to this hypothesis the plastic deformation of metals occurs when the equivalent stress reaches the value of the flow stress

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_\theta)^2]} = \sigma_f. \tag{5}$$

After substituting the radial stresses (2) in this formula a much simpler relationship is obtained

$$|(\sigma_\theta - \sigma_z)| = 1,15\sigma_f. \tag{6}$$

While the metal is flowing along the deformation zone it becomes increasingly work hardened, which is revealed by gradual increase in the flow stress σ_f. For the same reason the difference between the circumferential and the axial stresses is also increasing (Fig. 5). The dependence (6) allows finding one (σ_θ) from two unknown components of the stress state (σ_θ, σ_z). After its calculation and substitution to formula (4) the final form of the formula is obtained, which enables to calculate the hydrostatic pressures occurring in the deformation zone of the CEC processes

$$p_h = |\sigma_z| \pm 0,58\sigma_f, \qquad (7)$$

where the sign + refers to direct extrusion, and the sign – to radial extrusion. At the beginning of the process, the flow stress of the solution heat-treated 6082 alloy (W temper) is the lowest, being equal to σ_f=90 MPa. The absolute values of the axial stresses $|\sigma_z|$ in the deformation zone, situated in front of the die, assume values close to the extrusion pressure p_e=668 MPa, whereas behind the die – close to the back-pressure p_c=229 MPa (Table 1). Thus, accordingly to the derived formula (7) the smallest values of hydrostatic pressures p_h, occurring in the deformation zone at the beginning of the first cycle, are equal to p_h=720 MPa in front of the die, and p_h=177 MPa behind the die. The elements of the principal stress tensor T and its components: hydrostatic A and deviatoric D at the initial stage of the CEC process assume the following values (in MPa):

a) for deformation by direct extrusion

$$T\left\{\begin{matrix} \frac{\sigma_z}{(-668)} & 0 & 0 \\ 0 & \frac{\sigma_r}{(-720)} & 0 \\ 0 & 0 & \frac{\sigma_\theta}{(-772)} \end{matrix}\right\} = A\left\{\begin{matrix} \frac{\sigma_m}{(-720)} & 0 & 0 \\ 0 & \frac{\sigma_m}{(-720)} & 0 \\ 0 & 0 & \frac{\sigma_m}{(-720)} \end{matrix}\right\} + D\left\{\begin{matrix} \frac{\sigma_z-\sigma_m}{(52)} & 0 & 0 \\ 0 & \frac{\sigma_r-\sigma_m}{(0)} & 0 \\ 0 & 0 & \frac{\sigma_\theta-\sigma_m}{(-52)} \end{matrix}\right\} \qquad (8)$$

b) for deformation by radial extrusion

$$T\left\{\begin{matrix} \frac{\sigma_\theta}{(-668)} & 0 & 0 \\ 0 & \frac{\sigma_r}{(-177)} & 0 \\ 0 & 0 & \frac{\sigma_z}{(-229)} \end{matrix}\right\} = A\left\{\begin{matrix} \frac{\sigma_m}{(-177)} & 0 & 0 \\ 0 & \frac{\sigma_m}{(-177)} & 0 \\ 0 & 0 & \frac{\sigma_m}{(-177)} \end{matrix}\right\} + D\left\{\begin{matrix} \frac{\sigma_\theta-\sigma_m}{(52)} & 0 & 0 \\ 0 & \frac{\sigma_r-\sigma_m}{(0)} & 0 \\ 0 & 0 & \frac{\sigma_z-\sigma_m}{(-52)} \end{matrix}\right\} \qquad (9)$$

It follows from the above that radial extrusion is realized at the hydrostatic pressure considerably lower than in direct extrusion. Hence the first cracks may appear behind and not in front of the die.

Theoretically, the plastic deformation by the CEC method in frictionless conditions can be realized at minimal back-pressure, equal to $p_{c\_min} = \sigma_f$. However, this value is too small, as it is sufficient only for frictionless compression of the material flowing out of the die. From the presented experiment it can be seen that the required back-pressure (p_c=229 MPa) is considerably greater then the flow stress (σ_f=90 MPa). Such considerable difference between these parameters ($p_c >> \sigma_f$) results from the fact that the applied back-pressure should not only secure complete filling of the tool space behind the die, but also induce appropriately high hydrostatic pressure, not allowing the loss of cohesion of the processed material. At high hydrostatic pressure the favourable conditions for uniform deformation as well as formation of great many intersecting shear bands exists. Thanks to these conditions, by means of the CEC deformation method it is possible to obtain material of the same dimensions as at the beginning, but with a completely different new structure and very advantageous mechanical properties.

5. Summary

Experimental investigations presented above have shown that the new CEC machine with intelligent control back-pressure enables to obtain much more advantageous conditions of severe plastic deformation (SPD) in comparison with the initial device in which the back-pressure was regulated by means of screws.

On the basis of the performed experimental studies it has been found that the newly developed construction of tools guarantees very advantageous hydrodynamic conditions of lubrication. These conditions allow obtaining unique results of experimental investigations, which enable a detailed estimation of the directions of shear bands formation on the basis of traces appearing on the outer surface of the processed samples. It has been found that after cyclic, reversible plastic deformations of the solution heat-treated 6082 alloy, in the presence of high hydrostatic pressure, numerous, intersecting shear bands are formed. All the shear bands are formed at the angle of 45° to the extrusion direction, and their intersecting occurs at the angle of 90°. The value of the hydrostatic stress components has no influence on the directions of shear bands formation. However, application of low hydrostatic pressure contributes to the increase in the strain inhomogeneity and therefore promotes the occurrence of cracks within the shear bands.

On the basis of the directions of shear bands formation, determined experimentally, a very important conclusion has been formulated that in the deformation zone of the CEC processes there occurs the simple shear state of strain, corresponding to axial-circumferential and circumferential-axial simple shear. This conclusion enables to carry out a detailed analysis of the stress state occurring in CEC processes, together with the determination of the diagonal elements of the principal stress tensor and its hydrostatic and deviatoric components.

It can be supposed that at present, from among the known SPD methods, the CEC processing, realized on the unique hydrostatic press with intelligent control back-pressure, demonstrates the potentially greatest usefulness as an industrial process for the production of ultrafine grained materials.

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