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Equal channel angular extrusion of flat products

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Abstract

The paper considers equal channel angular extrusion (ECAE) of sufficiently long rectangular billets with different width-to-thickness ratios W/T. A stress analysis is performed inside plastic zone and inlet and outlet channels depending on contact friction and the billet geometry. Optimization of the processing mechanics and strategy to design tools are formulated. It is shown that flat billets with $W/T \gg 1$ provide important technical advantages for processing of massive slab-like billets and technology commercialization on the large metallurgical scale.

Keywords: ECAE; Optimization of processing; Flat products; Large scale commercialization

1. Introduction

The control of material structures by severe plastic deformation (SPD) presents significant scientific and practical interest. An important advantage of this approach is structure refinement to the sub-micron scale that can be attained in bulk billets, in a cost effective manner and for different metals and alloys. Such ultra-fine grained structures, usually in the range from a few microns to 0.2 micron, provide a reasonable compromise between high strength and satisfactory ductility that is especially attractive for structural applications. For commercialization of SPD substantial progress should be made in the related deformation techniques. The key factors are deformation method and optimization of processing characteristics. Irrespective of processing goal, material and temperature–strain rate conditions, the mechanics of SPD should provide intensive and uniform strains, simple shear deformation mode and low stresses. Among a few known methods of SPD, equal channel angular extrusion (ECAE) is presently considered as the most promising for industrial applications. However, realization of ECAE still remains imperfective. Despite of extensive activity in the field, absolute majority of the published works dealt with elongated billets as was originally described in [1]. These bars or rods like billets impose restrictions on materials, characteristics of ECAE and following processing. They are difficult to use as semi finished products and still there are no reports on process commercialization. In contrast, ECAE of flat billets followed by rolling, first introduced in [2], corresponds to universal products such as plates, sheets, strips and foils. Together with other technological advantages, this processing concept of ECAE presents great practical perspectives. While ECAE of elongated billets is now well investigated, special features of the ECAE of flat billets are not understood and were not disclosed in just a few related publications [3–5]. The present paper addresses some important details of the ECAE technology in the case of flat billets.

2. Processing mechanics

Lets consider ECAE of a rectangular billet (Fig. 1) with thickness T, width W and length L through sharp corner channels with tool angle 90°. Original 1 and final 2 billet positions are shown in Fig. 1 by long chain and solid lines, correspondingly. As the billet width W remains the same and the billet is moved inside the channels as a rigid body, the flow is near plane and the plastic zone is localized around a crossing plane of channels. It is known [6] that the stress–strain state and extension of the plastic zone strongly depend on boundary conditions imposed by an inlet channel 1 and an outlet channel 2. Thus, corresponding conditions should be analyzed first.

2.1. Inlet channel

At the beginning of ECAE, the well lubricated billet is placed into the inlet channel. An actual friction force depends on real

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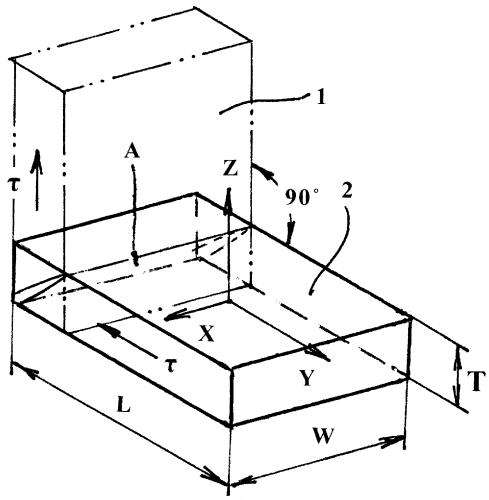

Fig. 1. ECAE of rectangular billets.

plastic contact and normal pressure between material and channel walls. Assuming that a stress state inside the channel is similar to linear plastic compression, the normal pressure σ_n on channel walls is (Fig. 2a)

$$\sigma_n \sim (p - Y)$$

where p is the axial pressure and Y is the material flow stress. If $p \sim Y$, the pressure $\sigma_n \sim 0$, and for long billets with $L/T \gg 1$ the plastic contact is formed by transverse buckling. Such irregular, local contact provides low friction force. If $p > 2Y$, the normal pressure $\sigma_n > Y$, and the plastic contact approximates to the full contact area between billet and channel. In this case, the same lubricant will result in large friction force and significant increment of pressure Δp along a channel length. Then, the extrusion pressure p_e is:

$$p_e = p_1 + \Delta p \tag{1}$$

where p_1 is the axial pressure at the channel entry. Experiments show that in all cases the increment of pressure Δp changes in the linear proportion with the channel length L. That allows one to suppose that effective plastic friction τ_1 is uniformly distributed and the Δp may be calculated by the formula:

$$\Delta p = \tau_1 f$$

Here f is a full contact area between billet and walls. When τ_1 is known for specific conditions, the maximum increment of the extrusion pressure in the stationary rectangular channel with four friction walls (Fig. 2a) is:

$$\frac{\Delta p}{Y} = \frac{(2n-1)(1+m)(\tau_1/Y)}{m} \tag{2}$$

Here parameters $n = L/T$ and $m = W/T$ define relative billet length and width. In particular, $m = 1$ corresponds to the ordinary case of long bar- or rod-like billets, $m \gg 1$ corresponds to flat plate-like billets and $m \ll 1$ corresponds to strip-like billets. Formulae (1) and (2) show that, depending on n and m, the extrusion pressure p_e may be significantly bigger than the material flow stress Y even for low friction τ_1.

The effective way to reduce contact friction, increase tool life and punch stability is via movable channel walls [7]. In one possible case (Fig. 2b, for detail see [7]), the inlet channel is formed by one stationary die wall and rectangular slot of the slider 2, which moves together with the billet 1. That way friction is eliminated along three channel walls. The maximum increment of extrusion pressure is:

$$\frac{\Delta p}{Y} = (n-1)\left(\frac{\tau_1}{Y}\right) \tag{3}$$

In another case (Fig. 2c), two side walls of the inlet channel are formed by movable sliders 2, 3 whereas back and front die walls are stationary. Correspondingly, the increment of the punch pressure is:

$$\frac{\Delta p}{Y} = (2n-1)\left(\frac{\tau_1}{Y}\right) \tag{4}$$

It is informative to compare results of formulae (2)–(4). In all cases, the extrusion pressure increases with the billet length-to-thickness ratio n. For effective processing, this ratio should be sufficiently large. Practically, n is selected between 4 and 8. The increment $\Delta p/Y$ is almost twice as large for Fig. 2c than for Fig. 2b. For the stationary channel (Fig. 2a), the extrusion pressure also strongly depends on the billet width-to-thickness ratio m. However, this ratio does not affect the extrusion pressure in both cases of movable channel walls. Calculated results for typical conditions $n = 6$, $\tau_1/Y = 0.15$ are shown on Fig. 3 in function of m. Three characteristic situations are outlined: (I) long billets ($m = 1$); (II) plate-like billets ($m \gg 1$); (III) strip-like billets ($m \ll 1$). It is evident that ECAE of long and, especially,

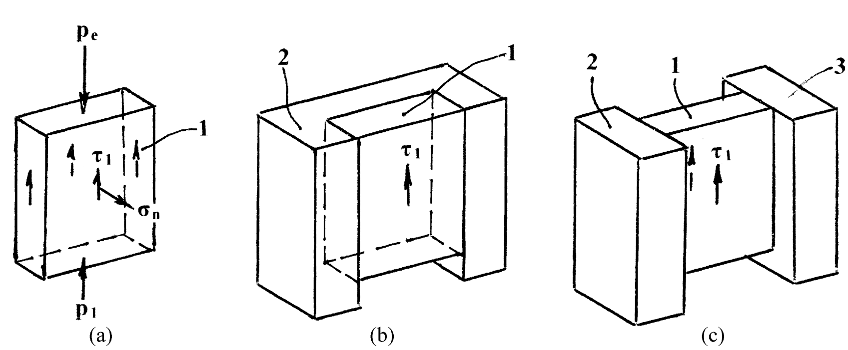

Fig. 2. Distribution of friction in inlet channels with: (a) stationary walls; (b) three movable walls; (c) two movable sidewalls.

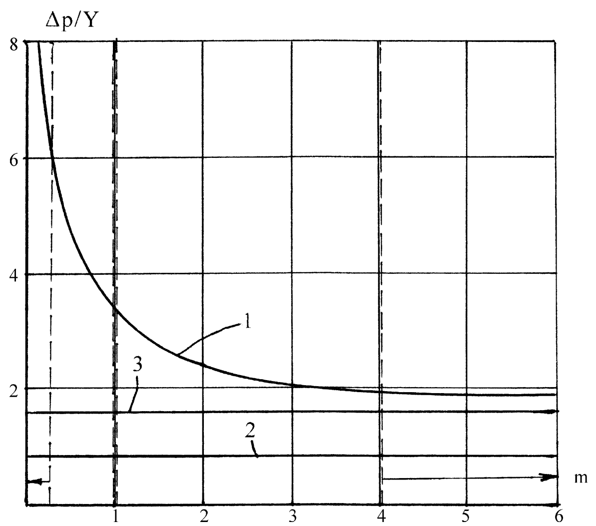

Fig. 3. Effect of billet ratio m on the increase of pressure along inlet channel ($L/T = 6$, $\tau_1/Y = 0.15$) with: (1) stationary walls; (2) three movable walls; (3) two movable walls.

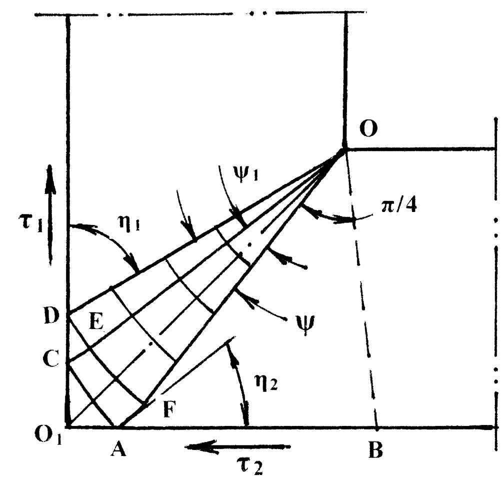

Fig. 5. Slip line solution with different friction in channels.

strip-like billets in stationary channels results in the multifold increase of the extrusion pressure in comparison with the flow stress Y. In these cases, ECAE of sufficiently large billets and hard materials can be performed only in dies with movable channel walls at powerful presses. However, for flat billets, two movable channel walls provide insignificant reduction of the extrusion pressure. Therefore, simple dies with stationary inlet channels and ordinary presses can be used in many cases of large flat billets.

2.2. Outlet channel

In contrast to the inlet channel, lubrication of the outlet channel is a challenging problem (Fig. 4a). Because of the sharp change in the extrusion direction, high normal pressure at the bottom wall, intensive slip and uncovering of the atomic clean material along a bottom contact surface O_1B, heavy scratches, sticking and galling can be observed even with the best lubricants [7]. That leads to high extrusion pressure, poor billet surface and intensive die wear. All these problems can be eliminated by using a movable slider along the bottom channel wall (Fig. 4b) [7]. That way plastic friction between material and die is substituted by elastic friction μ between slider 1 and guide Plate 2. During extrusion, the slider 1 usually remains free and some slip and shear stresses τ_2 should be developed along the billet contact surface O_1B to overcome friction between slider and a guide plate:

$$\tau_2 f_{O1B} = \mu p_1 WT \tag{5}$$

Here f_{O1B} is an area of the contact surface O_1B and μ is the coefficient of Coulomb's friction. At normal conditions, the slider speed is close to the extrusion speed. As friction is not a stable phenomenon, certain deviations in the slider movement may be observed. If stresses τ_2 exceed plastic friction between billet and slider, the flow becomes similar to the stationary die. Corresponding boundary conditions in the outlet channel do not provide a localized plastic zone and simple shear deformation mode necessary for effective processing [6]. Therefore, the coefficient μ should be sufficiently low.

2.3. Plastic deformation zone

Inlet and outlet channels define friction boundary conditions τ_1, τ_2 for the plastic zone. A slip line solution is shown on Fig. 5

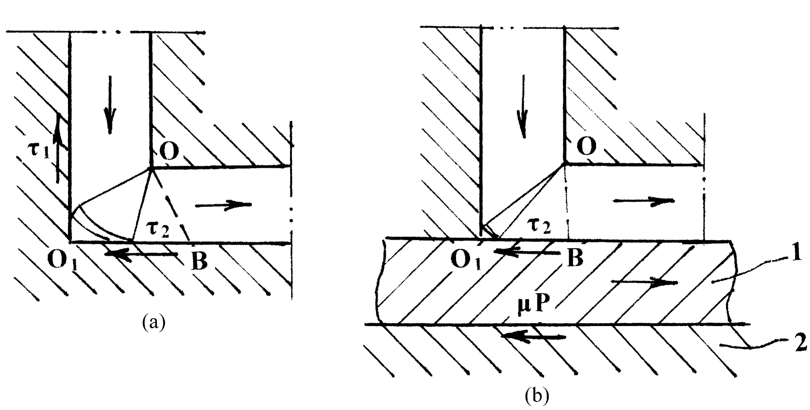

Fig. 4. Stationary outlet channel (a) and outlet channel with movable bottom wall (b).

for the case $\tau_1 > \tau_2$[1]. It is supposed that the material behavior is similar to the ideal plastic body[2] [8]. The slip line field includes central fan FEDO, mixed boundary area CDE and dead metal area O_1CA. The central angle of the dead area is:

$$\psi_1 = \eta_1 + \eta_2 - \pi \tag{6}$$

Angles η_1, η_2 are calculated by formulae [8]:

$$\eta_1 = \left[\frac{\pi - \text{Arccos}(\tau_1/k)}{2}\right], \quad \eta_2 = \left[\frac{\pi - \text{Arccos}(\tau_2/k)}{2}\right],$$

where $k = Y/\sqrt{3}$ is the material shear flow stress. Solutions for particular cases of τ_1, τ_2 were considered in [6].

Now we can gather results and outline the optimal strategy to design ECAE processing. First of all, note that the stationary outlet channel always induces the lubrication problem. In the limit situation $\tau_2 \to k$, $\tau_1 \to 0$, a slip line analysis [6,7] gives for the entry pressure at the inlet channel $p_1/Y \sim 2.3$. That results in full contact between billet and channel walls and leads to the high extrusion pressure p_e in all practical cases of long channels $L/T \gg 1$ and finite friction $\tau_1 > 0$. In fact, published data show that the extrusion pressure may be as high as $p/Y \sim 7$ [9]. For most materials at low processing temperatures, so large pressures are not admissible for modern tool alloys. Therefore, despite simplicity, stationary outlet channels are unpractical for industrial applications.

With a proper movable bottom wall of the outlet channel (Fig. 4b), friction τ_1, τ_2 and coefficient μ are small quantities. Under these conditions, the slip line field of Fig. 5 can be considered as a small modification of the "zero solution" when $\tau_1 = \tau_2 = \mu = \psi = 0$ and the plastic zone is the single slip line O_1O. Then, using the perturbation method for slip lines [10] and omitting intermediate results, with accuracy to the second order of magnitude, formulae (5) and (6) give:

$$\tau_2 \sim \mu Y, \quad \psi \sim \frac{(\tau_1 + \mu Y)}{k}$$

and the entry pressure inside the inlet channel is:

$$\frac{p_1}{Y} \sim \frac{2}{\sqrt{3}} + \frac{\tau_1}{Y} + \mu\left(1 + \frac{1}{2\sqrt{2}}\right) \tag{7}$$

In accordance with Eq. (7), there is a sufficient room for parameters τ_1 and μ to form the local contact between billet and inlet channel with low friction, if the increment of the extrusion pressure Δp also remains moderate. With movable outlet channel, the inlet channel may be performed as stationary (Fig. 2a) or with two movable walls (Fig. 2c). As was previously shown (Fig. 3), the simple stationary channel is effective for flat billets with the length-to-thickness ratio L/T more than four whereas for long billets ($L/T = 1$) and strip-like billets ($L/T \ll 1$) movable sidewalls are necessary. Therefore, only the first case will be further considered.

[1] An alternative solution for $\tau_1 < \tau_2$ follows from Fig. 4 by reversing an extrusion direction.

[2] This approximation is valid yet after the first pass.

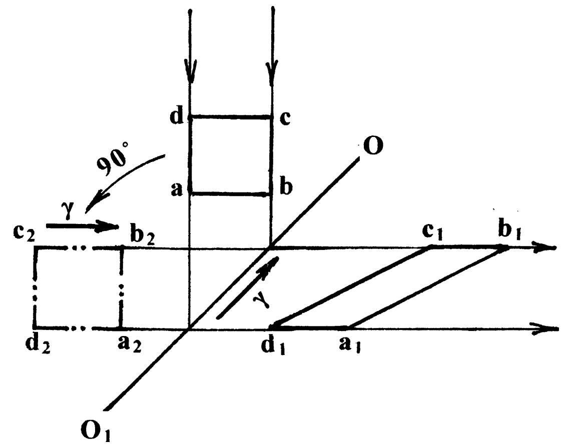

Fig. 6. Material distortion during one pass ECAE.

3. Multi-pass processing

3.1. Basic routes

To accumulate large shear strains and control their orientations, ECAE should be repeated a number of times with billet rotations about the axis of symmetry *X*, *Y*, *Z* (Fig. 1a) after each pass. For flat billets, the basic system of rotations or routes was introduced in [2][3]:

Route A—no rotation.
Route B—billet rotates alternatively ±90° about axis Z.
Route C—billet rotates 180° about axis Z;
Route D—billet rotates 90°into the same direction about axis *Z*.

During rotations, a square flat billets with $L = W$ is the most preferable because they can be processed into the same die with any rotation. Numerous combinations of possible rotations result in different microstructures, textures and properties. Although the basic routes provide the simplest systems of rotations (only around axis *Z*), other routes may be more beneficial in special cases. Some of them will be considered later.

3.2. Distortion of material elements

For low contact friction in both channels, the central angle ψ of the plastic zone (Fig. 5) is small. In this case, material straining during crossing the plastic zone includes mainly two simple shears along boundaries DO and AFO [6]. Approximately, such accumulated shear is equivalent to single shear $\gamma = 2$ along slip line O_1O of the corresponding "zero solution" when $\psi = 0$. Fig. 6 shows transformation of the "unit" material element *abcd* into parallelogram $a_1b_1c_1d_1$ caused by shear γ

[3] In the paper, we will use the same designation of routes like in [7] to underline that each basic route is independent from others. Similar routes but with different designation were also used in [3].

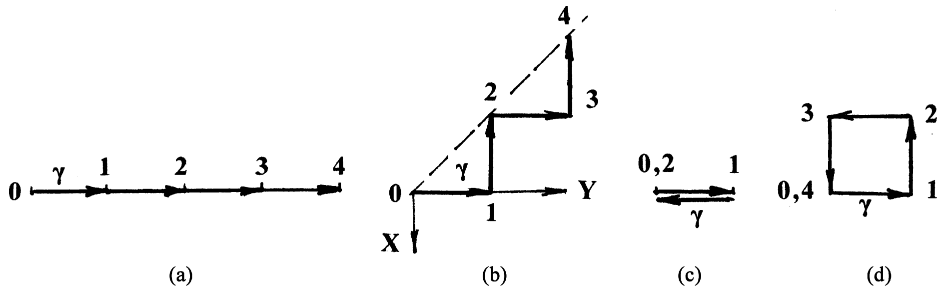

Fig. 7. Element displacements for routes A (a), B (b), C (c), and D (d).

along O_1O. One can see that the identical distortion is attained by rotating the element 90° from its original position *abcd* inside the inlet channel to the position $a_2b_2c_2d_2$ inside the outlet channel followed by shear γ into the flow direction. Such flow decomposition with fictitious shear along c_2b_2 is useful to calculate distortions during multi-pass ECAE because for flat billets all distortions take place into parallel planes to the billet's flat surface. This procedure is simplified by conserving the material position inside the outlet channel and applying successive vector shears $\boldsymbol{\gamma}_\mathbf{i}$ in corresponding flow directions at each pass for different routes. Because a transient motion does not effect the element distortion, it may be accepted that the bottom element side a_1d_1 is fixed and top side b_1c_1 is progressively transferred as whole on vectors $\boldsymbol{\gamma}_\mathbf{i}$ along parallel plane to the billet flat's surface. Final displacements after each pass are a vector sum of all preceding shears. Corresponding displacements and distortions of the "unit element" relative to the original coordinates *X*, *Y*, *Z* are presented on Figs. 7 and 8 for four passes of the basic routes. Routes A and C correspond to the plane flow and distortions are the same as in long billets [12]. Similarly, routes C and D provide cyclic loadings with restoration of element shape after each two and four passes, respectively. Maximum distortions with increased elongation and inclination to the flow direction *Y* are observed for route A. Distortions for route B are $\sqrt{2}$ times smaller than for route A and they are oriented at an angle of 45° to the axis *Y* after even numbered passes.

3.3. Shear planes and shear bands

The considered processing mechanics defines simple shear deformation mode and orientations of shear planes at each pass. Shear planes play an important role for multi-pass ECAE. At the first pass, they induce low angle cells and cell blocks strongly elongated along the shear direction O_1O (Fig. 5). During following passes, continuous plastic flow is substituted by micro-localized flow inside shear bands, which are collinear with a continual shear direction O_1O. Although structure refinement mechanisms of SPD are not well understood, there are numerous experimental confirmations for different materials and processing conditions (temperature, strain rate) that shear bands induces the largest portion of new high angle boundaries during ECAE. Additional mechanisms of structure refinement to the sub-micron and nano scale involve shear band intersections and rotation of the material fragments outlined by shear bands and cell boundaries. Therefore, intensity of refinement and morphology of the refined microstructure depend on the evolution of shear bands and high angle boundaries in the material during processing.

At each pass, micro-shear bands arise along corresponding macro-shear planes. At subsequent passes, shear bands remain stable structural formations that flow together with the material and change their orientations as the accompanying coordinate system. Positions of shear bands induced at any pass are defined by their distortions during following passes. For two successive

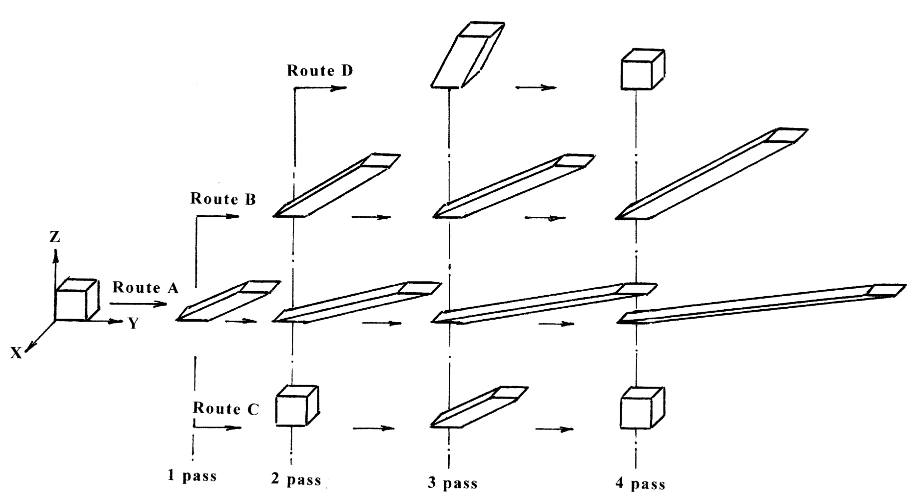

Fig. 8. Element distortions after four passes via routes A, B, C and D.

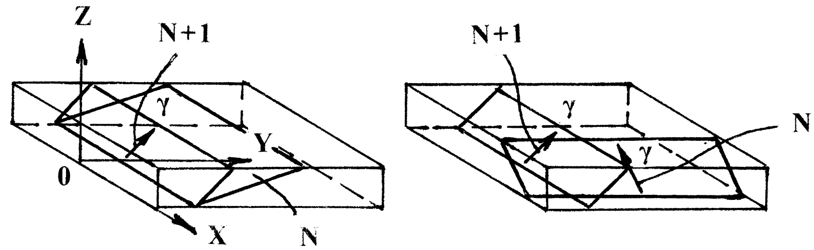

Fig. 9. Shear bands orientations after two successive passes without billet rotation (a) and with rotation 90° (b).

passes N and $(N+1)$ without rotation of flat billets, distortions of N shear bands are caused by $(N+1)$ shear (Fig. 9a). However, with billet rotation 90°, shears along perpendicular planes $(N+1)$ does not affect N shear bands (Fig. 9b). Therefore, during multi-pass processing of flat billets there are two independent systems of shear bands corresponding to deformation histories into X and Y directions. Calculated orientations of shear bands after four passes via basic routes are shown in Fig. 10 where numbers 1, 2, 3 and 4 designate positions of shear bands induced at first, second, third and fourth passes. For routes A and C, orientations of shear bands are similar to the related routes in the case of long billets [7]. For routes A (Fig. 10a) and B (Fig. 10b), shear bands progressively rotate to the extrusion direction. When a number of passes increases, the primary shear bands become difficult to distinguish. Their intersections will result in thin, elongated fragments with following subdivision by rotation. For route C (Fig. 10c), shear bands coincide with the same shear plane at any pass. It may be expected that in this case multiple cyclic loading will display fragment restoration and rotation with formation of equiaxial but coarser micro-structures than for routes A and B. Similarly, after four passes via route D (Fig. 10d), the material distortions are zero, shear bands coincide with macro shear planes and cyclic loading facilitates the fragment rotation. Routes B and D provide two families of mutually perpendicular shear bands favoring for development of three-dimensional structures. However, two additional families of shear bands for route B may lead to finer microstructure. It should be noted that during ECAE of flat billets via routes B and D, shear bands have different orientations and, probably, are less effective for structure refinement than identical routes for long billets [7].

The present analysis cannot be applied to large contact friction or round corner channels with the extensive plastic zone $\psi \gg 0$ (Fig. 4a). In these cases, simple shear along circular slip lines plays the important role and shear bands are oriented along axes X, Y as was shown in [6] and confirmed experimentally in [13]. Such situation is quite typical for ECAE with the stationary outlet channel and processing schedule “billet-by-billet” despite of the effective lubricants.

3.4. Other processing routes

The basic routes include only one rotation about axis Z. These routes do not provide three dimensional systems of near orthogonal shear bands necessary for developing of fine and equiaxial structures with a low number of passes. In these cases, top and bottom billet surfaces remain the same at each pass and multi-pass processing accumulates strain non-uniformity and residual stresses through thickness resulting in billet bowing during following rolling or forging. Also, specific surface defects may arise at the top billet surface. These shortcomings are eliminated by using more complicated routes with additional rotations about axes X and Y.

One such route designated as route E comprises eight passes. The first four passes are performed as the basic route D with rotation 90° about axis Z into the same direction at following passes. After this stage, the billet has zero distortions and two families of shear bands/high angle boundaries (Fig. 10d) are induced

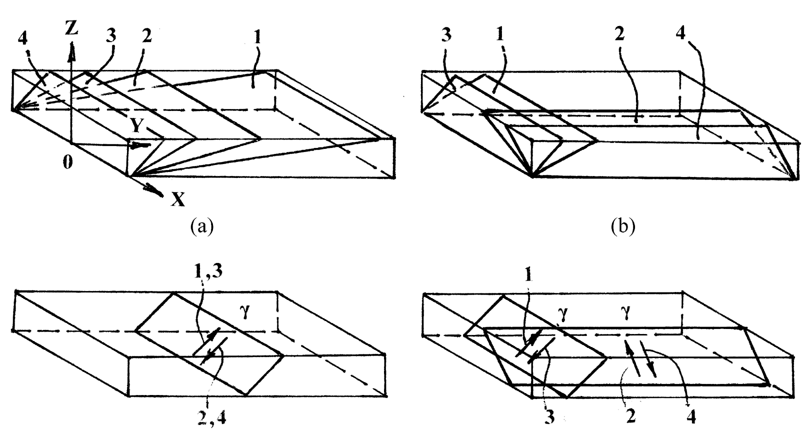

Fig. 10. Orientations of shear bands induced at first, second, third and fourth passes via routes A (a), B (b), C (c), and D (d).

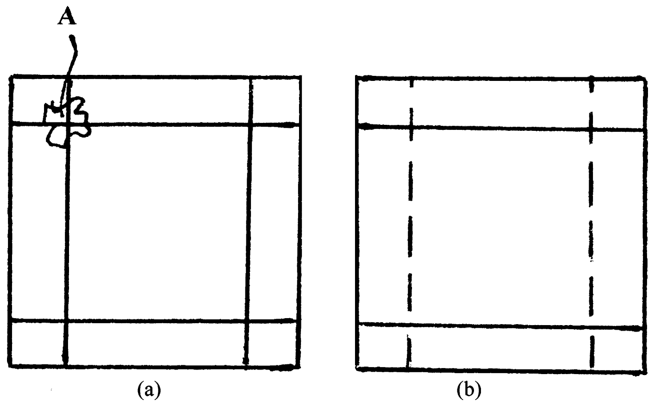

Fig. 11. Punch impressions at the billet top surface for routes D (a) and F (b).

into the material. Then, the billet is rotated 180° about axis *Y* (or *X*). That changes the orientations of shear planes and alternates top-bottom billet surfaces. Next four passes via route D again restores distortions and induces two new families of shear bands/high angle boundaries into perpendicular directions to the first shear bands. Therefore, route E develops four mutually perpendicular families of shear bands and conforms to the ideal route for structure refinement and homogenization of properties through thickness.

Another processing route, route F, eliminates specific irregularities of the structure near the top billet surface where a punch leaves a characteristic impression after each pass (Fig. 11). These impressions are tracks of shear planes with the sharp change of the flow direction. For multi-pass processing via routes D and B, track intersections form singular areas "A" (Fig. 11) where the plastic flow changes sharply into three perpendicular directions causing material weakening and micro-cracks. Route F includes second rotations 180° about axis *Y* together with the first rotations 90° about axis *Z* performed into alternative directions after each pass. That way, punch impressions are located at opposite sides of billet surfaces (Fig. 10b) and do not intersect each other whereas material distortions and shear band orientations remain similar to ordinary route D.

Other routes can also be introduced in special cases. In particular, two modifications of the basic route B similar to routes E and F are obvious.

4. Technological opportunities

The ultimate goal of any technological development is practical applications. Commercialization of ECAE was discussed in [7,14,15]. The main characteristic of ECAE is modification of material structures for simple geometrical forms. This approach is natural for fabrication of semi-finished products that may have numerous applications under conditions of competitive cost and simple conversion into final products. It appears from the above that ECAE may be very promising at the large metallurgical scale. However, ECAE of a "long billet" presents a few problems. Effective processing of long billets requires a complicated tool with movable walls into both channels. Massive long billets have much larger length than billets for ordinary extrusion of the same cross-section areas. In this case, the criteria for equipment selection is press stroke and daylight rather than load capacity. Thus, large and expensive presses and corresponding tool are needed for heavy long billets. Also, it is difficult to eliminate additional operations of billet trimming, reshaping and preheating between passes as well as to convert long billets into final products.

ECAE of flat billets resolves most of these problems. For the same billet length and *L*/*T* ratio, the weight of flat billets is from 4 to 8 times bigger than the weight of long billets with the corresponding increase of the press capacity. These parameters fit well to characteristics of modern extrusion presses providing the optimal use of press stroke, daylight and load. That significantly reduces requirements to the press and tool size and presents opportunity for processing of large metallurgical billets at existing equipment. Additionally, a simple tool with one movable wall of the outlet channel should be used. Large slab-like billets are easy to roll into plates, sheets, strips, foils and other flat products that have different applications in automotive, aerospace, transportation and other industries. It is not surprising that the first commercialization of ECAE was performed for flat billets (Honeywell Int., 2000) [16]. This still lone reported industrial application of severe plastic deformation proved technical visibility of ECAE for fabrication of bulk sub-micro grained materials. Recently, advanced ECAE of very large flat billets was developed at Engineering Performance Materials (EPM)[4]. The new processing technology improves material quality and eliminates billet trimming, reshaping and preheating between passes. It should be noted that widespread ECAE with billet ejection from a die by subsequent billets ("billet-by-billet") develops strong distortion of the back billet ends. To prevent laps during multi-pass processing, the distorted ends should be cut off after each pass resulting in a large material waste. The problem is eliminated by ECAE of separated (long or flat) billets with forced ejection [7]. There is also so called "end effect" that manifests itself in strain heterogeneity at billet ends. In the case of long billets, it may be spread through entire billet volume [17]. For ECAE of flat billets, corresponding heterogeneity of microstructure and texture is equalized by following rolling and, to some extent, may be removed during trimming of rolled products. The significant increase in productivity and material yield reduces the cost of multi-pass ECAE to a comparative level with ordinary metal forming operations.

5. Conclusions

Contact friction is the critical factor in engineering of ECAE. For rectangular billets, depending on billet ratios, the extrusion pressure may be inadmissibly high even for originally soft materials and with the best lubricants. For inlet channels with length-to-thickness ratios $L/T > 4$, the moderate extrusion pressure ($Y < p_e < 2Y$) provides an irregular, local plastic contact and a low friction whereas the high extrusion pressure ($p_e > 2Y$) results in full contact and the high friction. In all cases, a movable bottom wall of the outlet channel is an effective technical

[4] See http://www.epm-us.com.

solution to eliminate friction, material sticking and to reduce the extrusion pressure.

The billet width-to-thickness ratio W/T also has a notable effect on the extrusion pressure for long square ($W/T \sim 1$) and strip-like billets ($W/T \ll 1$). In these cases, the inlet channels with two movable walls are necessary to reduce the extrusion pressure. For flat billets with $W/T \gg 1$ this effect is insignificant and simple stationary inlet channels may be used.

The basic processing routes for flat billets lead to similar material distortions as in long square billets. However, routes B and D with spatial plastic flows provide different orientations of shear bands/high angle boundaries and are less effective than for long billets. Other processing routes, similar to considered routes E and D, should be introduced in special cases.

ECAE of bulk slab-like billets provides important technical advantages in fabrication of different flat products. This processing concept is cost effective, productive and preferable for large scale industrial commercialization.

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