FRACTURE MECHANISM IN THE PROCESS OF BAR ROLLED STOCK BREAKAGE

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ABSTRACT

This paper presents the results of the investigations carried out by the authors in the field of fracture mechanism of bar rolled stock while dividing it into billets using the breakage method. Step-by-step technique was developed, which allows to determine cumulative strain intensity of material points along their displacement paths and the direction of elemental crack extension on the basis of evolution regularities of a plastic enclave. The complete path of a through-thickness crack is formed by summing up elemental areas. New breakage methods were developed. They allow to control the crack path effectively and to obtain high-quality billets from various materials.

KEYWORDS

Stress concentrator, plasticity resource, crack path, three-point and cantilever breakage conditions.

INTRODUCTION

In machine-building the process of bar material division into billets in any loading conditions is accompanied by the development of sizable plastic deformation and the further nearly uncontrollable bar fracture. Plastic deformation of faces and an irrationally oriented crack reduce geometric accuracy of the obtained billets, that's why it's advisable to diminish the size of plastically deformed area and to create conditions for the controllable crack extension. The above problem can be successfully solved while dividing bar rolled stock by the breakage method.

The method consists in the following: stress concentrator 1 (Fig. 1)(V-shaped segmental or circumferencial notch) is made on bar 2 and then the bending load is applied to the weakened cross section. After some plastic deformation resulted from the bending of the billet, a through-thickness crack of fracture spreads out of the concentrator tip.

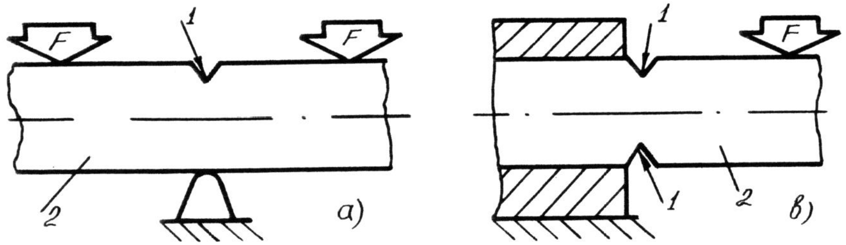

Fig. 1. Three-point (a) and cantilever (b) conditions of bar rolled stock breakage.

The most common are the T1, T2, C1, C2 loading conditions, where the letter corresponds to the first letter of the condition name - three-point (Fig. 1,a) or cantilever (Fig. 1,b), and the figure points out the number of segmental concentrators in each division plane.

INVESTIGATIONS TECHNIQUE

To determine the complete path of a through-thickness crack a technique was developed, in accordance with which the coordinates of the crack birth area and the directions of the crack extension were defined for every given moment of the fracture development. The technique is based upon the step-by-step analysis of the plasticity resource exhaustion degree in the deformation nidus and includes the successive accomplishment of the following stages: 1) investigation of the plastic yielding character; 2) construction of coordinated stress fields and points displacement velocity fields in a plastic enclave; 3) determination of points displacement paths; 4) determination of cumulative strain intensity along the displacement paths; 5) comparison of values of the cumulative strain intensity in the corresponding points with the diagram of plasticity of the divided material and determination of the direction of the elemental crack extension; 6) determination of the complete path by summing up elemental areas.

PLASTIC YIELDING REGULARITIES

Taking the works of Green (1953), Alexander and Komoly (1962), and others as a base, plastic bending of a strip with stress concentrators was investigated by the slip-line method (Kirilovski and Timoshchenko, 1990, 1991; Timoshchenko and Kirilovski, 1991). Let's point out the most important of the obtained results, regularities of plastic yielding in the area surrounding the stress concentrator tip having the greatest interest

among them.

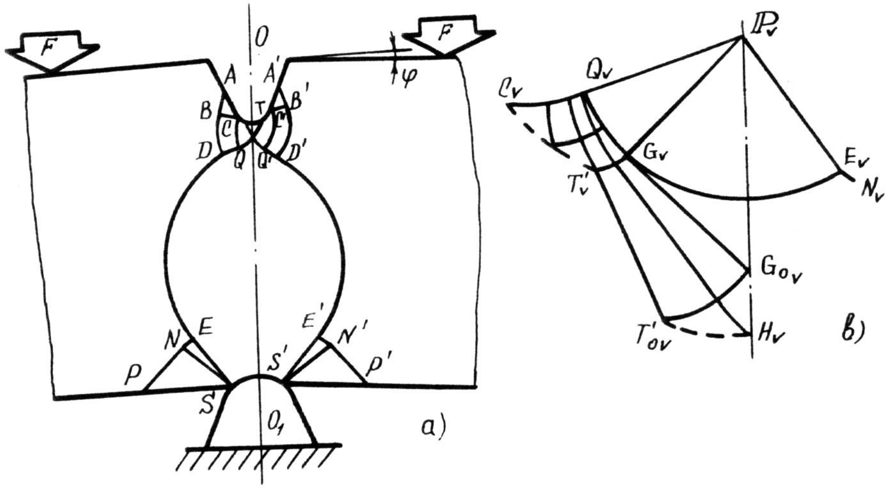

Fig. 2. Slip-line field (a) and hodograph (b) for the T1 condition.

In a three-point loading condition (Fig.2,a) the deformation nidus is symmetrical relative to the required division plane and is asymmetrical in a cantilever condition (Fig.3,a). Slip lines form the exponential spiral network CQT in the concentrator tip. In the middle part of the rolled stock cross section the deformation nidus is formed by isolated slip lines DE that are drawn along a circle arc. Supporting fixtures in the points of contact with rolled stock locally destroy contacting areas by the bearing strain. Plastic yielding bears a non-stationary character, the sizes of the deformation nidus increase with the increase of the bending angle φ . Slip-line field parameters during the evolution process of a plastic enclave are determined by solving the system of equations, where Hencky relationship, equilibrium equation $\Sigma F_x=0, \Sigma F_y=0$, $\Sigma M=0$ and geometrical dependencies binding up projections of the typical slip lines on the X and Y axes were included.

In constructing the velocity field simply corresponding to the stress field (Fig. 2,b and 3,b), the numerical solution of the initial characteristic problem was carried out. The above problem is reduced to the system of equations obtained on the basis of Geiringer relationships

$$z_\alpha^{m,n} = z_\alpha^{0,n} + \Delta_\alpha \left(z_\beta^{0,n} + \sum_{i=1}^{m-1} z_\beta^{i,n-1} + \Delta_\beta \sum_{i=1}^{m-1} z_\alpha^{i,n-1} \right)$$

$$z_\beta^{m,n} = z_\beta^{m,0} + \Delta_\beta \left(z_\alpha^{m,0} + \sum_{j=1}^{n-1} z_\alpha^{m-1,j} + \Delta_\alpha \sum_{j=1}^{n-1} z_\beta^{m-1,j} \right),$$

where $z_\alpha^{m,n}$ and $z_\beta^{m,n}$, $z_\alpha^{i,n-1}$ and $z_\beta^{m-1,j}$, $z_\alpha^{m-1,j}$ and $z_\beta^{m-1,j}$ are projections of the velocity in knots on the α and β axes relative to the (m,n),(i,n-1),(m-1,j) slip-line network; $v_\alpha^{c,n}$ and $v_\beta^{c,n}$, $v_\alpha^{m,o}$ and $v_\beta^{m,o}$ are projections of velocity knots (o,n),(o,m) on the α and β axes located on slip lines, where the velocity distribution laws are given $v_\alpha^{c,n} = v_\alpha(o,n)$, $v_\beta^{c,n} = v_\beta(o,n)$, $v_\alpha^{m,o} = v_\alpha(m,o)$, $v_\beta^{m,o} = v_\beta(m,o)$; $\Delta_\alpha = (\theta^{00} - \theta^{m0})/m$, $\Delta_\beta = (\theta^{00} - \theta^{0n})/n$ are elemental extention of the angle of rotation of the α- and β-lines within each cell; θ is the angle measured between the X axis and a tangent to the α-line in the corresponding knot; m and n are the number of cells along the α- and β-lines.

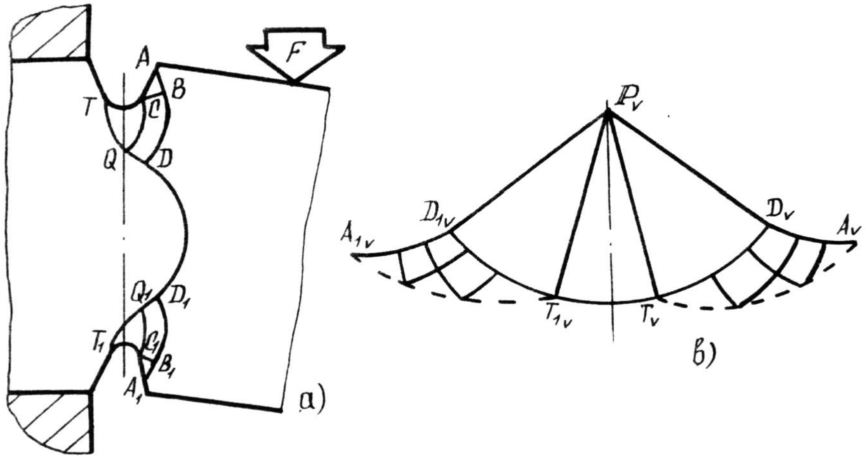

Fig. 3. Slip-line field (a) and hodograph (b) for the C2 condition.

From the point of view of the supposed crack births, exponential spiral areas CQT located in the concentrator tip in the tensionarea are of the greatest interest. Inthe process of plastic yielding,displacement paths of material points $u_1 = u_1(t)$, $u_2 = u_2(t)$ are formed out of instantaneous values of the principal displacements u_1, u_2 (t is time). Polar coordinates ρ_1, φ_1 of the corresponding point at a moment of time t+Δt were defined according to the formulae

$$\rho_1 = (u_1 + \Delta r \cdot \sin\varphi)/\sin(\varphi_1 - \varphi) = (u_1 + \rho - \Delta r \cdot \cos\varphi)/\cos(\varphi_1 - \varphi),$$

$$\varphi_1 = \varphi + \operatorname{arctg}[(u_1 - \Delta r \cdot \sin\varphi)/(u_2 + \rho - \Delta r \cdot \cos\varphi)],$$

where ρ, φ are polar coordinates at a moment of time t ; Δr is the change of the concentrator tip radius.

STRAIN INTENSITY

The estimation of the instantaneous value of strain intensity ε_i was made, taking into account displacement paths and velocity field parameters

$$\varepsilon_i = 2/\sqrt{3}\,\varepsilon_1 \approx [v_1^{j+1}(t) - v_1^{j}(t)]\,\Delta t/\Delta S_1,$$

where ε_1 is the principal deformation, $v_1^{j}(t)$, $v_1^{j+1}(t)$ are projections of velocities of material points j and j+1 on the principal axis S_1 at a moment of time t; $\Delta S_1 = S_1^{j+1}(t) - S_1^{j}(t)$ is the change of the S_1 coordinate while moving from the j point to the j+1 point along S_1.

When determining the cumulative strain intensity $\Sigma\varepsilon_i$, the proportional summing up of instantaneous values ε_i along the point displacement path was carried out. In the coordinates $\ln\varepsilon_i$, η the above process of summing up is reflected in the function $\Sigma\varepsilon_i = \Sigma\varepsilon_i(t)$, $\eta = \eta(t)$ called the deformation accumulation path ($\eta = \sigma/\tau_i$ is the index of the stress condition; σ is the average stress; τ_i is the shearing stress intensity).

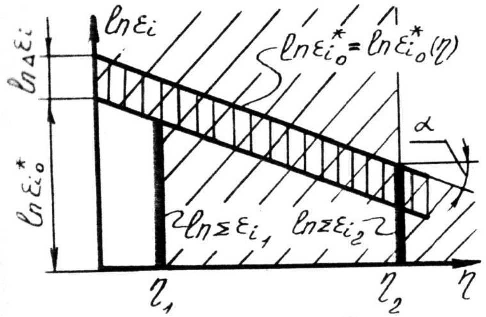

Fig.4. Influence of ε_{io}^* on the coordinates of cracking.

The dependence of the initial local plasticity ε_{io}^* upon η is characterised by the plasticity diagram $\varepsilon_{io}^* = \varepsilon_{io}^*(\eta)$ (Fig.4), which in the same coordinates $\ln\varepsilon_i$, η has the form of a straight line inclining at the α angle to the η axis:

$$tg\,\alpha = [\ln(1-\psi) + \varepsilon_{io}^*(\eta_i)]/(1-\eta_i),$$

where ψ is the standard value of the unit lateral contraction of the area; ε_{io}^* (η_i) is the initial local plasticity of a material at an arbitrary value η_i (it is defined during tests).

The strain intensity value accumulated by the moment of time t+Δt in the given point of a body was defined according to the formula

$$\Sigma\varepsilon_i(t+\Delta t) = \varepsilon_i + \Sigma\varepsilon_i(t)\cdot\varepsilon_{io}^*(t+\Delta t)/\varepsilon_{io}^*(t),$$

where $\Sigma\varepsilon_i$(t), $\Sigma\varepsilon_i$(t+Δt) is the strain intensity accumulated by the moments of time t and $t+\Delta t$; $\varepsilon^{*}_{i_o}(t)$, $\varepsilon^{*}_{i_o}(t+\Delta t)$ is the initial local material plasticity which corresponds to the indices of the stress condition taking place in the given point at the moments of time t and $t+\Delta t$. By local plasticity ε^{*}_{i} is meant the true value of the limited plasticity that any material point of a deformable body possesses. The value ε^{*}_{i} represents a part of the initial local material plasticity $\varepsilon^{*}_{i_o}$ remaining in the examined point after a definite share of the plasticity resource $\varepsilon^{*}_{i} = \varepsilon^{*}_{i_o} - \Sigma\,\varepsilon_{i}$ is exhausted. Cracking takes place when $\varepsilon^{*}_{i} = 0$.

Depending on the plasticity diagram level and the angle of its inclination, the initial crack may be formed in various points of the plastic enclave. Let's define points 1 and 2 where the crack birth is presupposed. The indices of the stress condition in these points are $\eta_1 < \eta_2$, and the cumulative strain intensity is $\Sigma\,\varepsilon_{i_1}$, $\Sigma\,\varepsilon_{i_2}$ (Fig.4). Let's mark the range, within which the plasticity diagram can change its position, resulting from variations in plastic properties of a material, as $\Delta\varepsilon_i$. When $\Sigma\,\varepsilon_{i_1} \leq \Sigma\,\varepsilon_{i_2}$, a crack is always formed in point 2. For the fracture to take place in point 2 and not in point 1, when $\Sigma\,\varepsilon_{i_1} > \Sigma\,\varepsilon_{i_2}$, the following conditions should be observed

$$\ln\{\Sigma\,\varepsilon_{i_1}[\Delta\varepsilon_i - \ln(1-\psi)]/\Sigma\,\varepsilon_{i_2}[-\ln(1-\psi)]\} + (\eta_1 - \eta_2)\,\mathrm{tg}\,\alpha \leq 0.$$

Moreover, the plasticity diagram should be located inside the cross-hatched area.

The α angle should be more flat to have the guaranteed fracture in point 1:

$$\ln\{[\ln(1-\psi) - \Delta\varepsilon_i]\,\Sigma\,\varepsilon_{i_2}/\ln(1-\psi)\cdot\Sigma\,\varepsilon_{i_1}\} + (\eta_1 - \eta_2)\,\mathrm{tg}\,\alpha \leq 0.$$

In a three-point condition of bar rolled stock breakage, the initial cracking is more likely to be connected with the G and Q points displacement paths (Fig.5,a). The distribution analysis $\Sigma\,\varepsilon_i$ showed that the ratio between $\Sigma\,\varepsilon_{i_G}$ and $\Sigma\,\varepsilon_{i_Q}$ is identical to that shown in Fig.4, i.e. $\Sigma\,\varepsilon_{i_G} > \Sigma\,\varepsilon_{i_Q}$, $\eta_G < \eta_Q$ ($\Sigma\,\varepsilon_{i_G}$ and $\Sigma\,\varepsilon_{i_Q}$ are cumulative strain intensities in material points of rolled stock that coincide with G and Q points at the initial moment of deforming). That's why a crack is formed in the G point in the materials with low and flat plasticity diagram. The initial crack area spreads along the GT initial velocity discontinuity line and along GO_1 the G point path during the process of plastic bending of bar rolled stock (dot line). Further, plastic yielding regularities are maintained, but now it is the crack extending along the symmetry axis that

plays the role of the stress concentrator. Its deflection from the OO_1 axis is only possible when going onto the external surface near the support.

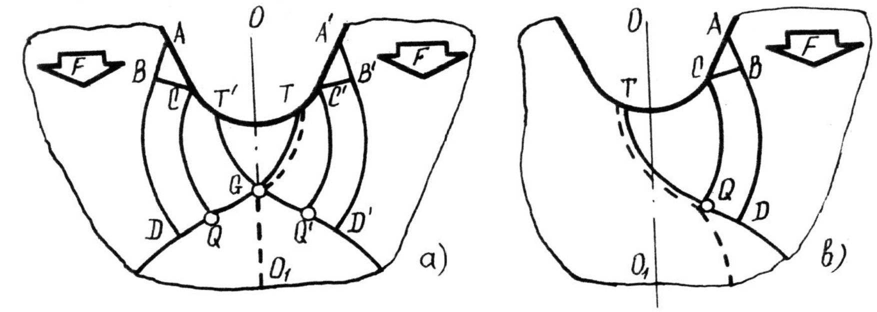

Fig.5. Initial section of the crack path in the three-point(a) and cantilever(b) breakage conditions.

Materials with the steep plasticity diagram are less favourable for division in conventional breakage conditions, as the crack birth takes place in the Q point which doesn't coincide with the symmetry axis. The further path is also unstable and can result in the reduction of the quality of billet faces. The deformation nidus asymmetry in the cantilever loading conditions (Fig.5,b) also gives rise to cracking in the Q point and to its development outside the symmetry axis.

APPLICATION OF THE INVESTIGATIONS RESULTS

On the basis of the obtained results the rational ways of controlling the breakage process were determined. They involve the following: 1) recommendations on the choice of the most effective loading in the given conditions; 2) setting optimum geometric parameters of the concentrator, supporting fixtures and the parameters characterising the coordinates of the load application point; 3) selection of the expedient temperature-velocity loading conditions; 4) indication of favourable directions and ways of change of plasticity of the divided materials.

The above recommendations are realised in a range of new effective loading condition, in which concentrator and breakage performance operations are combined within one die and are carried out on general-purpose presses at the production rate of up to 200 billets per minute. High-quality billets out of various grades of materials were obtained (Fig.6). Attainable geometric parameters are: billet length $L \geq 0.3d$ (d is the bar diameter); face deviation from perpendicularity to the longitudinal axis is (0.005-0.01)d; face deviation from flatness is (0.008-0.04)d.

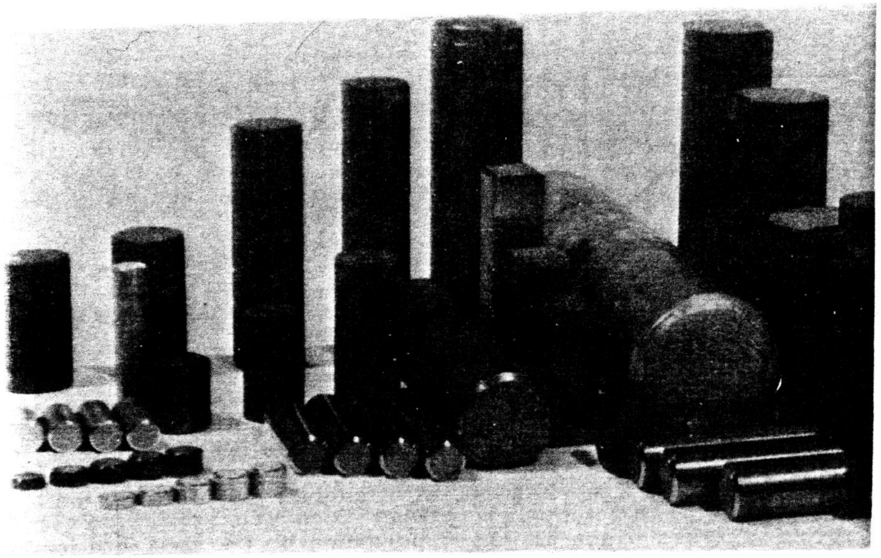

Fig.6. Billets obtained by rolled stock breakage.

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