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PROGRESS IN ROLLING MILL TECHNOLOGIES

There are a significant number of physical and chemical impact methods for the metallic materials during the processes of crystallization, deformation, and heat treatment, leading to the refinement of the structure. However, traditional technologies for the fabrication of metallic materials often result in the coarse-grained structure, as most of them employ processing temperatures, at which the resulting small grains are unstable. From the severe plastic-deformation point of view, traditional rolling has a significant drawback, limiting its use for obtaining the ultrafine-grained structure in materials. Thus, total accumulated deformation is limited during conventional rolling by the multiple decreases in rolled blank thickness. In this regard, in recent years, several specialized rolling methods, which allow eliminating this drawback, were proposed.

Keywords: rolling, severe plastic deformation, ultrafine-grained structure, microstructure.

1. Introduction

One of the most common methods of producing items from non-ferrous metals and alloys is longitudinal rolling (Fig. 1), which is used to get sheets and strips in hot and cold conditions, as well as to produce profiles and wire. Rolling, as the next stage or an independent method, is widely used due to its high productivity and relative simplicity. Thus, a modern sheet rolling mill is capable of processing tens of thousands of tons of steel per month, reducing sheet thickness from 200–300 mm to 2–5 mm. For rolled products, the rod diameter can be reduced from 100–200 mm to 10–20 mm [1]. In this case, the grain can be refined by 5–10 times, which

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for ordinary steels gives a value of about 10–20 μm. Porosity is practically reduced to zero, and mechanical properties are improved due to strengthening and alignment of the structure. Rolling is economical in large-scale production; its metal consumption and energy costs are lower than forging comparable-sized blanks. The rolling scheme is shown in Fig. 1.

During the process of rolling, the workpiece cross-section decreases, width and length increase. The cross-sectional shape of the resulting product depends on the rolls' shape. For example, sheets, strips and tape are rolled on smooth rolls. In the so-called calibrated rolls, circles, squares, hexagons, rails, angles, *etc.* are rolled. To produce pipes, balls, gears and other profiles, special rolling mills are used, in which more than two rolls are used; the shape of rolls can be conical, helical, *etc.* [3–9].

Traditional rolling, despite its prevalence and efficiency in metal processing, has significant limitations in obtaining an ultrafine-grained (UFG) structure of material. The key disadvantage is the limited accumulation of plastic deformation. In the process of conventional rolling, total deformation is achieved by multiple reductions of the billet thickness. However, this method leads to a relatively low level of deformation per unit pass, which is insufficient to form a UFG structure, which requires significant accumulation of crystal lattice defects and, as a result, a high dislocation density that stimulates recrystallization and formation of a fine-grained microstructure. Grain size in material is inversely proportional to the dislocation density achieved during deformation. With the higher dislocation density, there are the finer grains [10–13].

To overcome this limitation and achieve a UFG structure, over the last decade, specialized rolling methods that significantly increase the total accumulated deformation have been developed. These methods are focused on increasing the intensity of deformation in a single pass, rather than repeating the process many times with a slight decrease in thickness [8, 9, 14–16].

In addition, the efficiency of achieving the UFG structure depends on many factors, including rolling temperature, deformation rate, type and composition of material, as well as shafts and workpiece geometric parameters. Optimization of these parameters allows achieving the maximum effect from the use of specialized rolling methods and obtaining a material with unique properties, such as increased strength, wear resistance and plasticity. Further

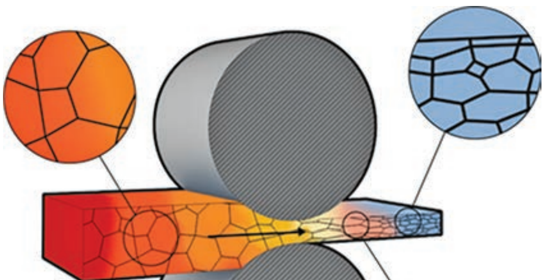


Fig. 1. Rolling scheme [2]

research is aimed at improving existing methods and developing new ones that can even more effectively form the UFG structure in various materials.

2. Asymmetric Rolling

The study of the structure and mechanical properties of steels processed by equal-channel angular pressing (ECAP) is also an urgent problem in materials science. Low plastic properties and high probability of brittle fracture during pressing make it difficult to carry out ECAP of steels; proportion of edge destroyed volume of material with cracks and 'ridges' and unusable defective workpieces increases. To implement successfully ECAP, a few technological techniques are usually used to reduce the likelihood of defects, such as increasing pressing temperature, using backpressure, rounding the angle between the channels, optimizing pressure and pressing speed.

The main disadvantage of many methods is the need to use specialized equipment and/or a deforming tool to implement them. Therefore, one of the most promising and highly effective methods for obtaining a UFG structure is asymmetric rolling [17], which differs from the traditional one only in that the workpiece is deformed between rolls of different diameters or rolls rotating at different speeds. Asymmetric rolling can produce items with the UFG and nanostructure (NS). This is primarily due to the intensity of shear deformations developed during the deformation process. The diagram of the asymmetric rolling process is shown in Fig. 2, where two rolls of the same diameter rotate towards each other at different speeds with simultaneous deformation of the strip in the gap between rolls.

An asymmetric rolling process is a process in which there is no complete symmetry relative to the horizontal plane, *i.e.*, diameters of working rolls are different, the condition of their surface is different, or one of the rolls is non-driven, there are also options in which the rolls have different speeds, *etc.*

This rolling method allows controlling the shape of the rolled product, reducing rolling force, and obtaining UFG and NS metal products with improved mechanical properties. The most important advantage of asymmetric rolling is the possibility of its implementation on modern units without their complete reconstruction. Schematically, the variants of asymmetric rolling can be presented as follows (Fig. 3) [19]: (*a*) at different roll rotation speeds; (*b*) at different roll diameters; (*c*) at one non-driven roll.

The advantage of asymmetric rolling at different roll rotation speeds (Fig. 3, *a*) is the direct regulation of roll rotation speed, while the disadvantage is the need to use additional electric motors and gearboxes.

The advantage of the asymmetric rolling option in rolls of different diameters (Fig. 3, *b*) is that there is no need to use additional equipment, but the disadvantage is the impossibility of choosing the ratio of rolling

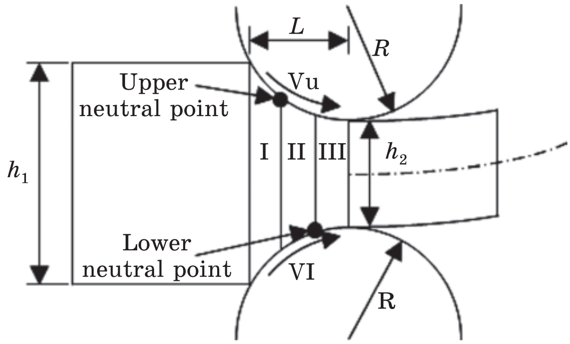


Fig. 2. Schematic diagram of asymmetric rolling process [18]

speeds on the lower and upper rolls.

As with equal-channel angular pressing (ECAP), different deformation routes are used in asymmetric rolling (Fig. 4).

In the work [20], the influence of asymmetric rolling on the texture and value of the Lankford coefficient *r* of AA5052 aluminium was investigated. A high degree of shear texture component distribution across the entire strip cross-section was achieved with asymmetric rolling and high reduction ratios. In addition, shear texture components were retained after annealing at 275 °C for one hour and remained almost unchanged after annealing at 400 °C for 30 minutes. The results show that the magnitude of plastic deformation by shear *r* increased by 1.4–1.7 times compared to conventional rolling.

Later, in Ref. [21], the effect of rolling parameters on the formation of shear texture in AA1050-O aluminium specimens was investigated. Using experimental and finite element method (FEM) data, they found that the optimal velocity asymmetry coefficient was of 1.5, for which shear strain was most characteristic over the entire strip cross-section.

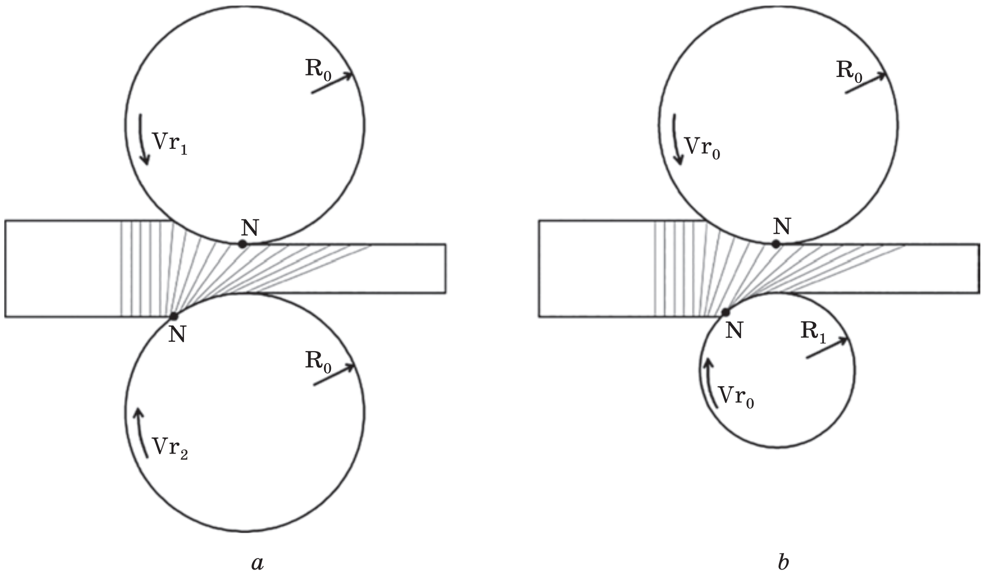


Fig. 3. Q Scheme of asymmetric rolling implementation: (*a*) for the case of identical roll diameters and (*b*) for the case of different roll diameters [19] ua

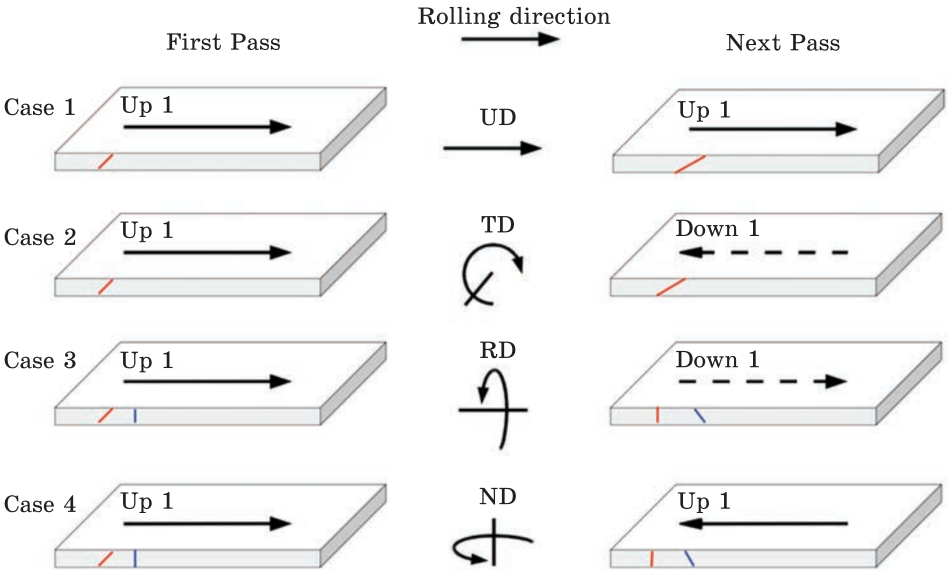


Fig. 4. Routes for asymmetric rolling: case 1 — no rotation; case 2 — work piece rotation in the transverse direction; case 3 — work piece rotation in the longitudinal direction; case 4 — work piece rotation around the normal axis [19]

They also found that the reduction value was a critical factor. Using FEM modelling, in Ref. [21], the effect of shear strain evolution was investigated during conventional and asymmetric rolling. They found that during conventional rolling, the strip underwent positive and negative shear strain before and after the neutral cross-section. However, during asymmetric rolling, the neutral cross-section moved toward the exit from the deformation zone; thus, shear strain was always positive. Using the shear strain history determined for conventional and asymmetric rolling for a certain number of finite elements, the authors of Ref. [21] calculated the resulting crystallographic textures. It was found that the ideal shear texture is closely related to the reverse shear deformation. Thus, an ideal shear texture cannot be formed by unidirectional rolling, but only by changing the rolling direction in each pass.

In the work [22], asymmetric rolling was investigated using steel sheets to evaluate the influence of different asymmetric rolling combinations on the deformation pattern and, consequently, texture. In addition, they investigated the influence of some routes (RD, TD, and ND) on the formation of an ideal shear texture. Their findings correspond to those obtained using aluminium alloys.

In Ref. [23], asymmetric rolling of AA5052 aluminium alloy was performed using a single driven roll with two passes, each with a reduction of 50%. The rolling process was carried out at 260 °C, and a traditional route (longitudinal) was used for comparison. The friction coefficient was increased by adding aluminium powder in an ethanol solution to rolls surface. They obtained a strip with a {001}⟨110⟩ texture, which was distributed after annealing, resulting in a random orientation of the structure. The resulting *r* value was close to 1 with a small variation, which is greater than in conventional rolling.

In Ref. [24], asymmetric rolling of AA5754 aluminium was used. A 2.5 mm thick strip was rolled at different speed ratios (1.5 and 2) with and without reversal between passes. The total reduction was of 56% in 2 passes. They obtained a texture change, but not a shear texture. This led to texture randomization and reduced longitudinal anisotropy, but the *r* value did not change.

In Ref. [25], asymmetric rolling of AA1050 and AA5754 aluminium samples was performed using a speed ratio of two. Despite a 50% reduction in each pass, the texture was slightly closer to the ideal shear texture. The average *r* value increased after recrystallization (during which texture components were detected, but the Δr value increased, also indicating undesirable anisotropy). In addition to changing the texture, asymmetric rolling is used as a grain refinement method, since it causes severe plastic deformation (SPD) in the strip deformation zone.

In the work [26], asymmetric rolling as an alternative to traditional SPD methods for grain refinement in pure aluminium was used. They confirmed their conclusion about the deformation mechanism through grain rotation using electron scanning diffractometry data by calculating the grain misorientation. Scientists tested reduction value several values of 65.2, 85.5, and 92.3%. Rolling was carried out at a speed ratio of 1.4 and a reduction of 0.2 mm per pass. They found that asymmetric rolling allows obtaining a fine-grained structure (less than 0.2 µm) even at a relatively low value of total reduction at annealing temperatures of 200 °C.

They compared samples obtained by asymmetric and conventional rolling with reduction ratios of 91.3% and 65.2%. Despite the high deformation ratios, samples deformed by conventional technology had a low degree of high-angle grain misorientation, and thus grain refinement, compared to asymmetric rolling. Thus, the authors concluded that shear deformation is very important in grain refinement and that unidirectional loading alone cannot sufficiently refine the grains.

In asymmetric rolling, working rolls draw in the strip, friction occurs between roll-strip pair, and the strip is gradually compressed, decreasing in thickness as it moves (Fig. 5).

Due to geometric conditions, the point on the strip surface at the entrance to the rolls has a lower speed than the peripheral speed of the rolls. After the strip is captured, it is drawn between the rolls by friction and compressed. When leaving the rolls, the surface speed of the strip exceeds the peripheral speed of the rolls, since the strip increases in the longitudinal direction and the thickness decreases.

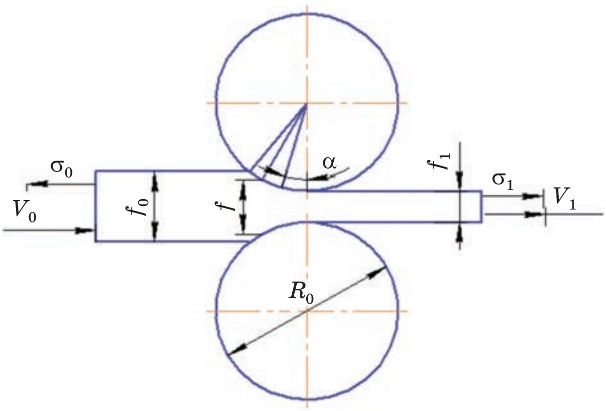


Fig. 5. Rolling process and its parameters

As a result, intermediate points arise for which the strip surface speed and roll peripheral speed are equal. These points are called neutral points (n.p.). Before the n.p., friction between the strip surface and the roll causes it to move forward. After the n.p., the strip speed is higher than the roll speed, and friction acts in the opposite direction. Position of n.p. varies depending on rolling conditions. At high reductions, n.p. will move towards the exit, which leads to increased friction and, consequently, to an increase in rolling power.

To analyse the rolling process, independent process variables must be identified. The most important ones are: E—elastic modulus of rolls; m and μ—friction factor and friction coefficient; R_0—roll radius; t_0 and t_1—sheet thicknesses at the entrance and exit of rolls ($r = t_1/t_0$); V_r—peripheral speed of roll; σ_0—resistance to deformation of material; σ_{x1} and σ_{x0}—front and rear strip tension.

On the side of slow roll, peripheral speed in the contact zone will be lower than strip speed, and the moment will be negative on the slow roll. Thus, an opposite force arises on the slow roll, which leads to the neutral point moving towards the exit from the rolls. On the side of fast roll, these parameters will be higher. Consequently, the upper fast roll will take up the full rolling force, compensating for the negative moment on the slow roll. Thus, the peripheral speed of the roll will be higher than the strip speed at the roll input over the entire contact surface. In this case, the neutral point will move towards the exit, and the speed difference will lead to the occurrence of shear deformations over the strip entire thickness. The neutral point is not symmetrical, which leads to the occurrence of shear deformations.

3. Cross-Roll Rolling

One way to eliminate the need for multiple workpiece deformations during rolling is to intensify the process by increasing the proportion of shear deformations. This can be achieved by sheet blank deforming in work rolls whose axes are rotated in the plane of the sheet at an angle relative to the transverse direction (Fig. 6). This method is known as oblique rolling [27].

It is generally accepted that a flat deformed state takes place during conventional rolling, while a volumetric deformation pattern is observed during oblique rolling, since angular (shear) deformations are different from zero. In this case, resulting shear deformations significantly increase the energy of shaping compared to traditional rolling, which leads to the formation of an ultrafine-grained structure with an average grain size of up to 600 nm (Fig. 7).

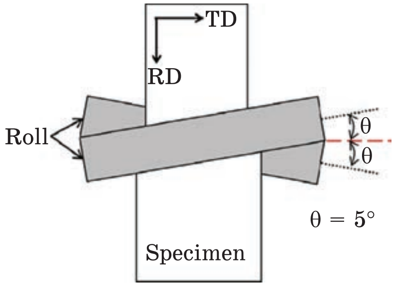


Fig. 6. Cross-roll rolling scheme [27]

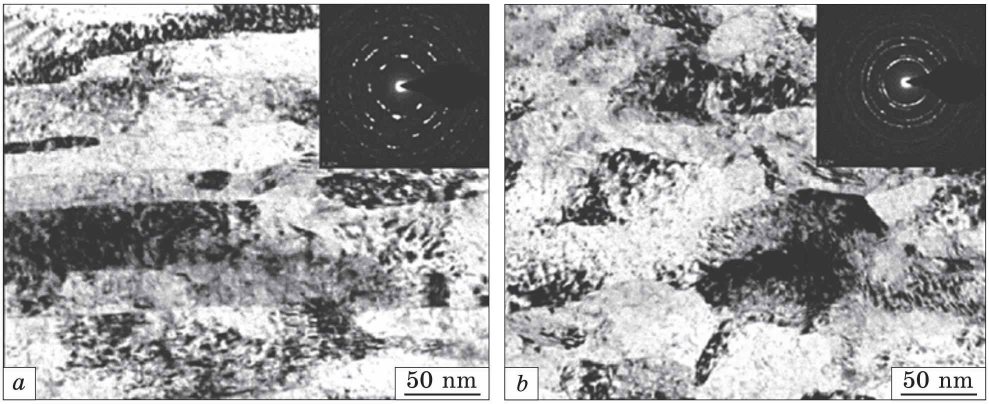


Fig. 7. TEM images of (*a*) conventional rolled material and (*b*) material after oblique rolling [27]

4. Rolling in Rolls with Reverse Taper

Rolling in rolls with reverse taper is a specialized method of metal processing, which allows achieving a significant improvement in the homogeneity of physical and mechanical properties in the finished strip. In contrast to traditional rolling, where the metal flows mainly in one direction, in this case, a more uniform, non-directional flow of material along the longitudinal axis of the strip is provided. This is achieved due to the specific geometry of the working rolls.

The key difference of the method is the reverse taper of the rolls. In conventional rolling, the rolls can be cylindrical or straight tapered, *i.e.*, the diameter increases or decreases smoothly along the roll axis. In the case of reverse taper, the roll diameter first decreases, reaching a minimum value in the middle, and then increases again. This creates a complex pattern of metal deformation, where zones of maximum and minimum pressure alternate, preventing the formation of longitudinal inhomogeneities in structure and properties.

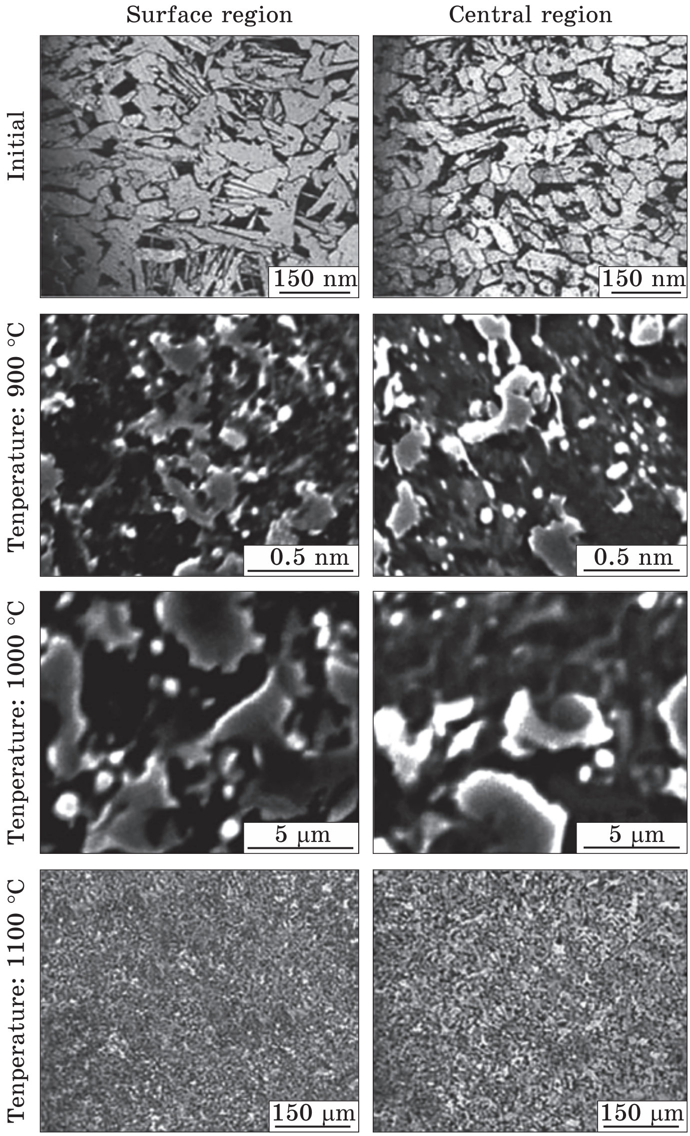


Fig. 8. Steel microstructure after three passes of asymmetric rolling in cone-shaped rolls at different temperatures [28]

The parameter determining the degree of reverse taper is calculated using the formula $K = (D - d)/(2L)$, where D is the diameter of the larger roll base, d is the diameter of the smaller base, and L is the length of the roll barrel. The value of the K coefficient directly affects the character of the metal flow and, consequently, the final properties of the strip. Large values of K lead to more intensive processing of metal in the middle part, which can be both an advantage (for example, to obtain higher strength in the centre) and a disadvantage (increased risk of defects). The optimum value of K is determined experimentally and depends on many factors, including the steel grade, the desired properties of the finished product, and the technological capabilities of the equipment.

In addition, such parameters as rolling speed, metal temperature, roll lubrication, *etc.* affect the efficiency of rolling with reverse taper. Proper selection of these parameters allows minimizing internal stresses in the strip and obtaining more stable results. The use of special lubricants, such as high-temperature compositions with improved adhesion properties, can reduce friction and roll wear, as well as improve the surface quality of the finished strip. Precise control of metal temperature during the rolling process ensures optimal deformation conditions and prevents undesirable structural changes.

Modern automated rolling control systems allow the control of all these parameters in real time, optimizing the process and ensuring high repeatability of results. As a result, reverse taper rolling is used in the production of high-quality steel for demanding structures where high homogeneity of properties throughout the material is required. This is particularly relevant to produce strips used in aerospace, mechanical engineering, and other industries where material reliability and durability are critical. Further research in this area is aimed at developing new methods for modelling the rolling process and optimizing the parameters to achieve even higher quality indicators of finished products.

Work [28] and Fig. 8 show the effect of this technology on the steel microstructure.

5. Longitudinal Rolling with Transverse Shear

Another method for intensifying shear deformation during rolling is longitudinal rolling with forced transverse workpiece displacement [29]. To implement this method, a special two-roll rolling mill was developed, the distinctive feature of which is the individual drive of each working roll from a hydraulic servomotor. In this case, the lower working roll, in addition to rotation, also receives axial reciprocating movements from a hydraulic vibrator. A computer is used to control the oil supply from the hydraulic station to the vibrator and servomotors, which synchronizes rotation and axial oscillations of rolls (Fig. 9, *a*).

As can be seen in Fig. 9, *b*, the developed mill provides very favourable conditions for SPD. Thus, when rolls rotate, large compressive stresses arise in the material, and reciprocating movements of the lower roll in the direction perpendicular to the rolling direction lead to shear deformations. Therefore, during longitudinal rolling with transverse shear, an intensive widening of the strip is observed.

Using this method, as a result of AA6061 alloy deformation nanostructure shown in Fig. 10 was obtained.

In this case, the main parameters influencing the process of structure formation are the reduction degree, the coefficient of friction between rolls and workpiece, frequency and amplitude of lower roll oscillations. In

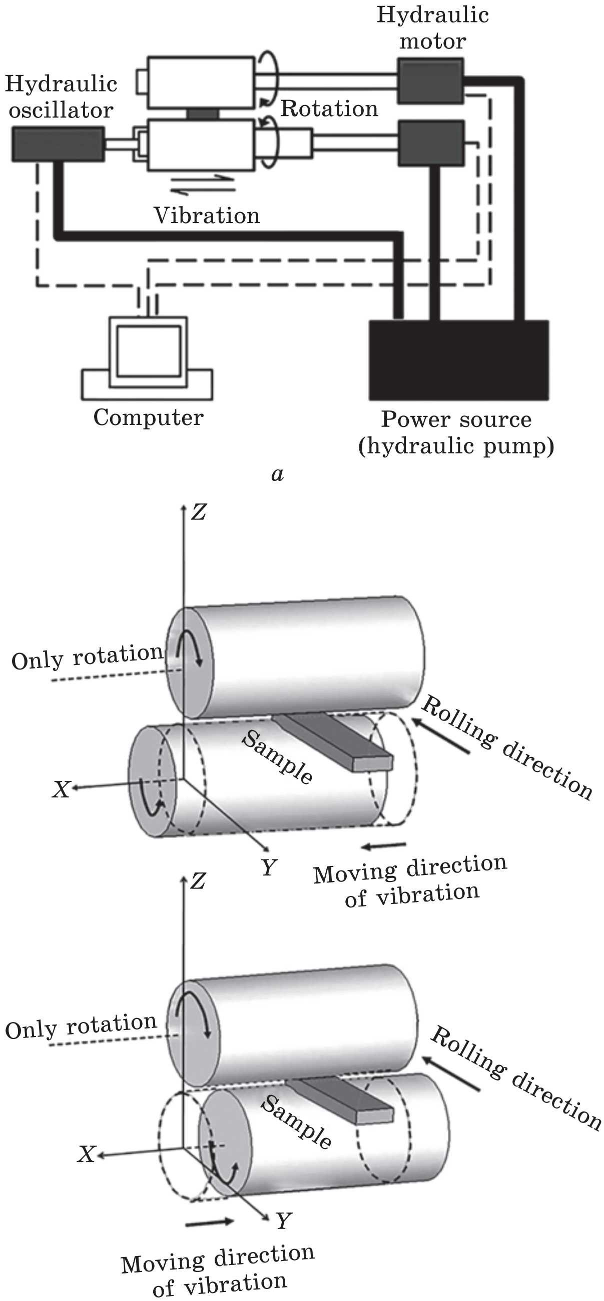


Fig. 9. Longitudinal rolling with transverse shear [29]

this case, the amount of reduction per pass must be large enough so that the friction forces arising during rolling ensure not only the capture and feeding of metal into the deformation zone, but also the shear of material during the axial displacement of the lower roll.

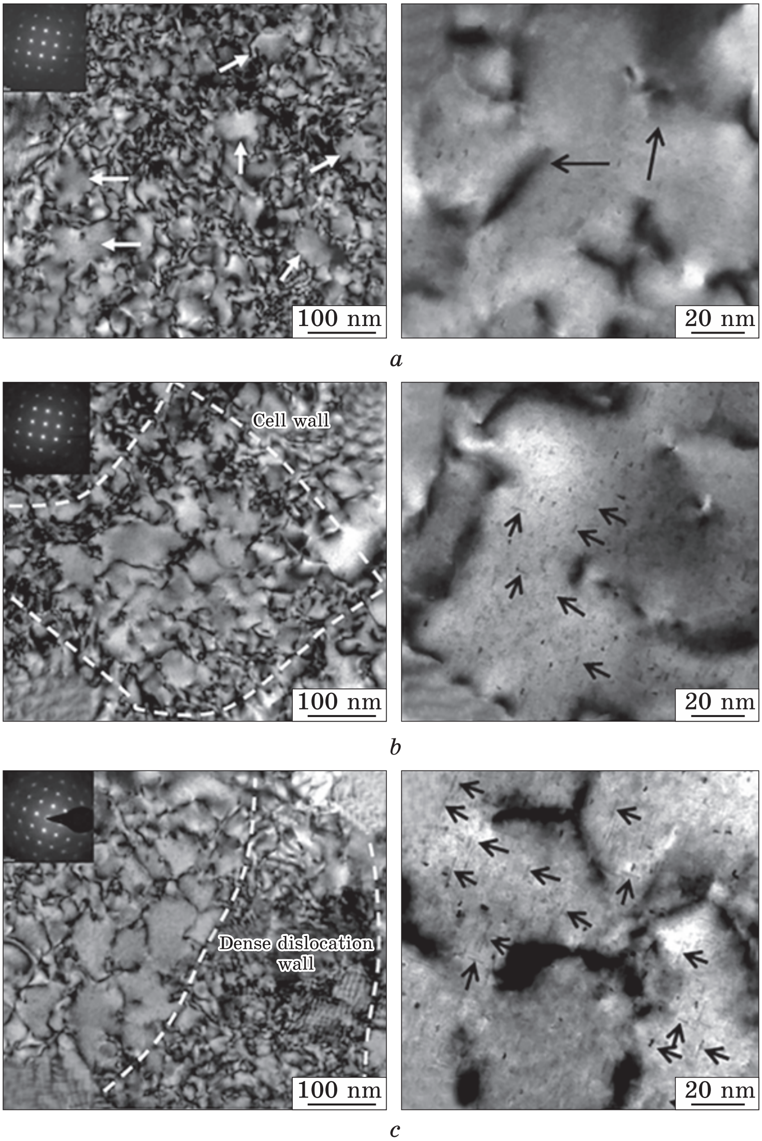
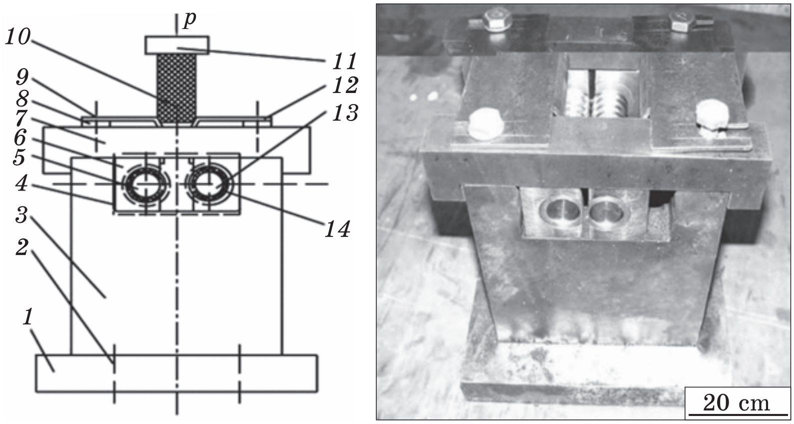


Fig. 10. Microstructure of samples processed by longitudinal rolling with transverse shear with an amplitude of 1.5 mm (*a*); ageing at 100 °C for 2 h, then ageing at 130 °C for 4 h (*b*); ageing at 100 °C for 2 h, then ageing at 130 °C for 18 h (*c*) [29]

6. Rolling in Grooved Rolls

Obtaining a UFG structure and improving mechanical and functional properties is possible with sequential rolling in corrugated and flat rolls. The method includes multipass compression of a flat blank by thickness with the formation of ribs on its surfaces by a pair of rolls with encircling pro-



a *b*

Fig. 11. Rolling in grooved rolls [30]

trusions, and subsequent multi-pass compression in smooth rolls. Formation of a fine-grained structure in the rolled product is ensured by the fact that encircling protrusions are made on the roll barrel half-length, and between passes, the blank is rotated in its plane by an angle of 180°, and ribs 3–20 mm high are formed on the blank surface. Alternating compressions with rotation of the blank between passes ensure multi-cycle transformation of blank surfaces from a ribbed state to a smooth one, and vice versa. Resulting macroscopic deformations lead to deep mechanical processing of the blank, grinding of crystallites, and dispersion of microstructure grains. This, in turn, ensures the formation of a fine-grained structure in sheet metal products.

A disadvantage of the method described above is that it is only applicable to the processing of fairly thick sheets. It is known a method for thin sheets and strips rolling, in which shear deformations occur due to intensification of the flow of workpiece metal transverse to the rolling direction [30]. The method consists of rolling a thin sheet between corrugated and smooth rolls, which results in a local decrease in thickness of individual sections and extrusion of metal part into the space between projections (Fig. 11). On the second and subsequent passes, an unevenness of thickness in cross-section and waves are eliminated by rolling in smooth rolls. In this case, it is possible to increase significantly the share of transverse deformations, so when rolling a strip 100 mm wide and 1 mm thick with 90% compression, the widening was 5 mm.

7. Accumulating Rolling with Connection

Accumulative rolling with connection (APC) can be used in the continuous process of sheet UFG materials production using the capabilities of conventional rolling equipment. At the same time, unlike the already considered methods of SPD based on the rolling process, during APC, there is no reduction in transverse dimensions of processed products, which allows for virtually unlimited accumulation of deformations in the material.

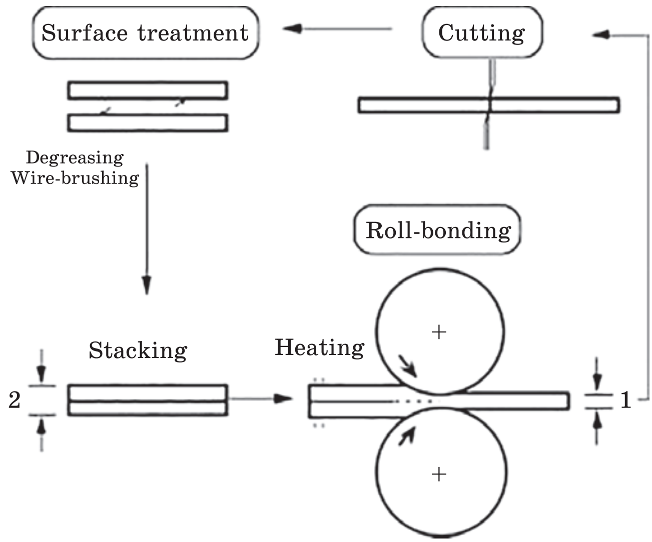


Fig. 12. Accumulative Roll-Bonding Process [31]

Figure 12 shows the APC scheme. Two sheets with a cleaned and degreased surface are folded into a package, which is rolled with a one-time compression of at least 50% to ensure the connection of individual layers. Then the resulting strip, consisting of two welded layers, is cut into two parts, the connecting sides of which are cleaned, folded into a package, heated and rolled again. The process is repeated until a specified number of rolling cycles is achieved.

To obtain a single solid body in the end, accumulated connection by rolling must be not only a deformation process, but also a process of joining materials due to forced diffusion in thin near-surface layers. For better joining, the surface of sheet materials is thoroughly cleaned.

In addition, this rolling method is sometimes carried out at elevated deformation temperatures (but below the recrystallization temperature) for better connection of blanks and reduction of the rolling forces.

The APC process uses standard rolling equipment. The process is carried out in such a way that the strip is compressed in height by a value equal to half its thickness in the original state [32]. Next, the resulting strip is cut in half and the halves are bonded together, after which a repeated rolling cycle is performed to a thickness equal to half of the original. The process is accompanied by bonded surfaces cleaning. Rolling is carried out until certain high degrees of deformation are accumulated. The ratio for calculating the equivalent deformation from the number of passes N looks like $\varepsilon_N = 0.8N$ [33].

The problem is that the grains are unevenly oriented. The grains are elongated in the transverse direction.

Conforming-type schemes have been developed in recent years [34]. The Conform™ technology developed by BWE is an innovative method of continuous extrusion that allows virtually unlimited length products to be manufactured from various metals and alloys. The process is based on the

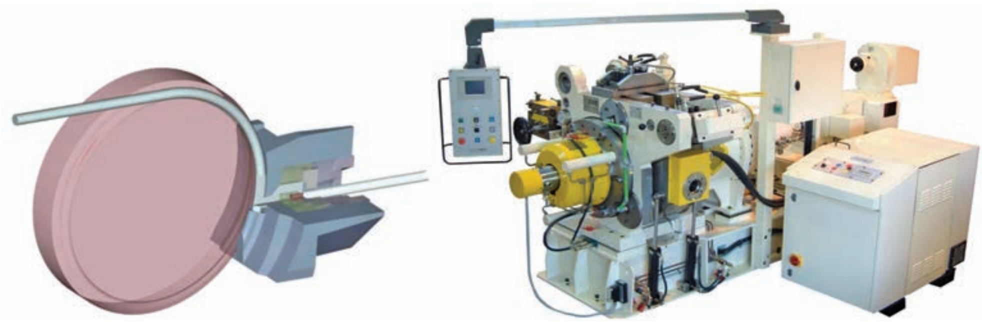


Fig. 13. Conforming 350i process [34]

use of a rotating disc with a peripheral groove. This disc serves as the driving force, feeding the raw material into the pressing chamber. Simple but effective design ensures a continuous process and high productivity.

Let us consider the operation mechanism in more detail. The raw material, usually in the form of a rod, is fed into the groove of a rotating disk. In the pressing chamber, limited by a shoe, there is a projection interacting with the groove of the disk. Rotation of the disk leads to the fact that material from the groove, getting into the contact zone with the projection, is pushed under pressure into the pressing chamber. From the chamber, material exits through a die, forming a product of a given profile (Fig. 13) [34].

It is important to note that although rods are the most common form of raw material, Conform technology allows the use of different morphologies of materials; the main condition is that the dimensions correspond to the disc groove. This opens wide opportunities for the use of secondary raw materials, such as scraps or granules, which helps reduce costs and improve the environmental friendliness of production.

Conforming ‘i’ series machines, the induction heating system was patented. This system provides fast and efficient direct heating of the displacement zone, minimizing heat loss and increasing energy efficiency of the process. Preheating the chamber to operating temperature before starting the machine reduces the load on the tool and allows working with materials that require higher temperatures and complex profiles. Precise temperature control also helps improve product quality and reduce defects.

Separately, it is worth mentioning process modification ‘Conklad’, designed for the production of bimetallic products. This technology uses two rods of different materials fed into the chamber from both sides. This ensures the ‘envelopment’ of one material by another, forming a composite product with specified properties. For example, it is possible to create a conductor with high electrical conductivity and a strong protective shell. Conklad allows for both direct application of shell and application of coat-

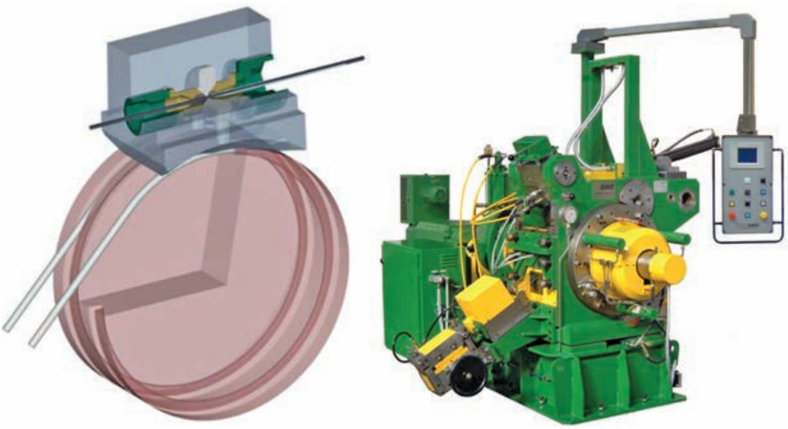


Fig. 14. Conklad process [34]

ing directly to the core, ensuring precision control of coating thickness and uniformity (Fig. 14).

One of the long-blank producing methods is the technology known as Linex, developed by specialists from Western Electric Company. This method involves continuous pressing, which is carried out due to the force of active friction arising between the flat surfaces of the chain links, as well as the upper and lower planes of the workpiece, which has a rectangular cross-section. It is important to note that the value of pressure in this process depends on the difference in friction forces on the lubricated and non-lubricated areas of the blank. Linex technology is used, in particular, to produce aluminium bus bars and wire at plants such as 'Venscuck' in the U.S.A. However, it is worth emphasizing that the maximum value of the drawing coefficient when using this method is an order of magnitude less than when using the Conform technology, which is one of the main disadvantages of Linex.

Almost all the listed methods (except ECAP-Conform and some other works [35–50]), despite their advantages and innovative potential, are not aimed at obtaining a UFG structure, and their application is limited to non-ferrous metals only.

For the purposeful formation of a wide range of materials UFG structure, a continuous combined method of 'rolling–pressing' was invented using a stepped ECA matrix [51]. The same authors [52] have an idea of 'casting–rolling–ECAP' combined process. Both methods are shown in Fig. 15.

Theoretical study and justification of the first process were conducted in work [54], experimental study of aluminium rolling–pressing processed in work [55]. After only three cycles of continuous pressing, it was possible to achieve grain refinement from 180 μm to 3.5 μm. The method is aimed at energy-saving production of UFG structure; however, it does not allow for developing the required level of deformation degree

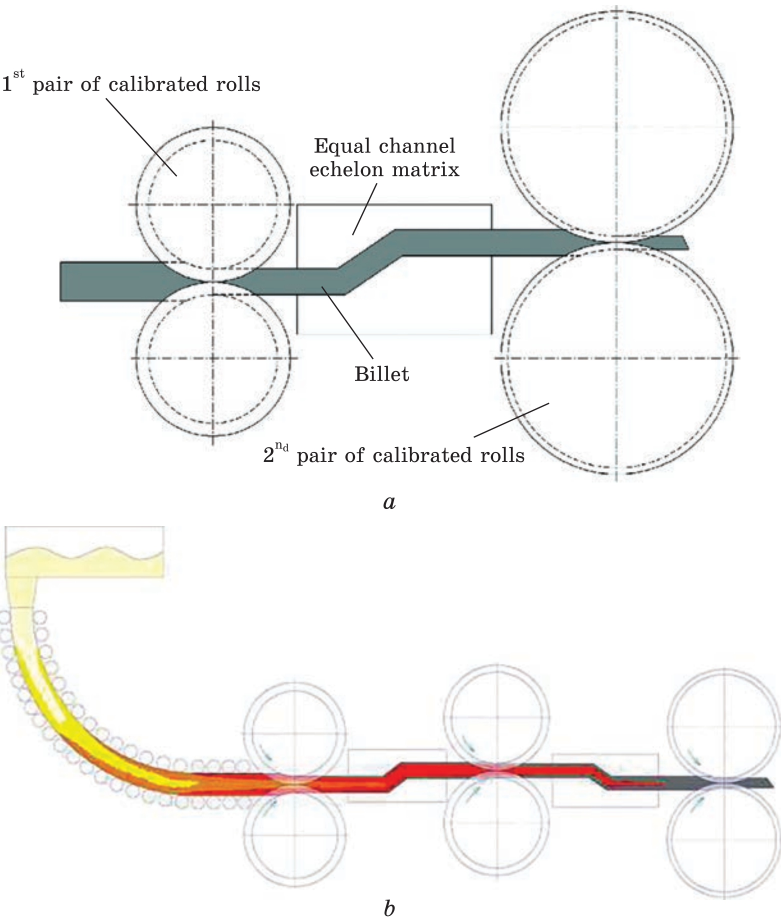


Fig. 15. Combined processes with continuous ECAP: *a* — rolling–pressing [6]; *b* — casting–rolling–ECAP [53]

in one pass, and the shape of the obtained product is limited to a rectangular cross-section.

8. Methods of Wire Deformation

The study presented in Ref. [56] examines evolution of copper wire microstructure and mechanical properties subjected to deformation during work with a rotating equal-channel step die and subsequent drawing (Fig. 16). It was obtained an ultrafine-grained gradient microstructure as a result of experiments, which has a high proportion of high-angle grain boundaries (Fig. 17). This discovery is of great importance for the construction industry, since the use of such hardened copper wire can significantly reduce the weight of structures by decreasing the wire diameter, which, in turn, can lead to material savings and improved performance.

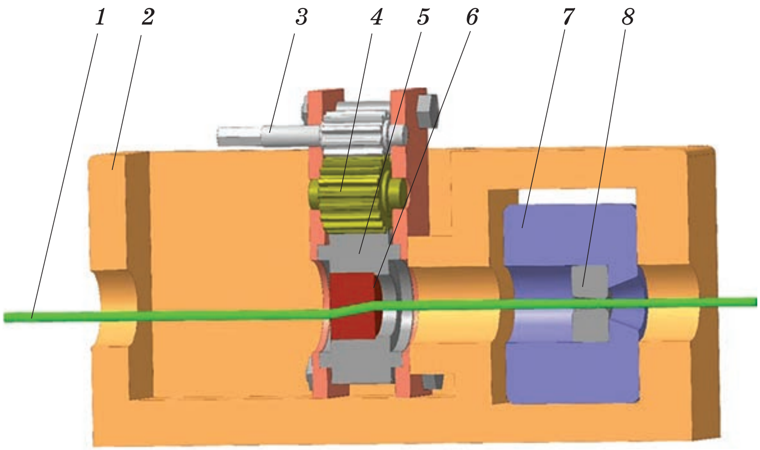


Fig. 16. Wire deformation diagram [56]

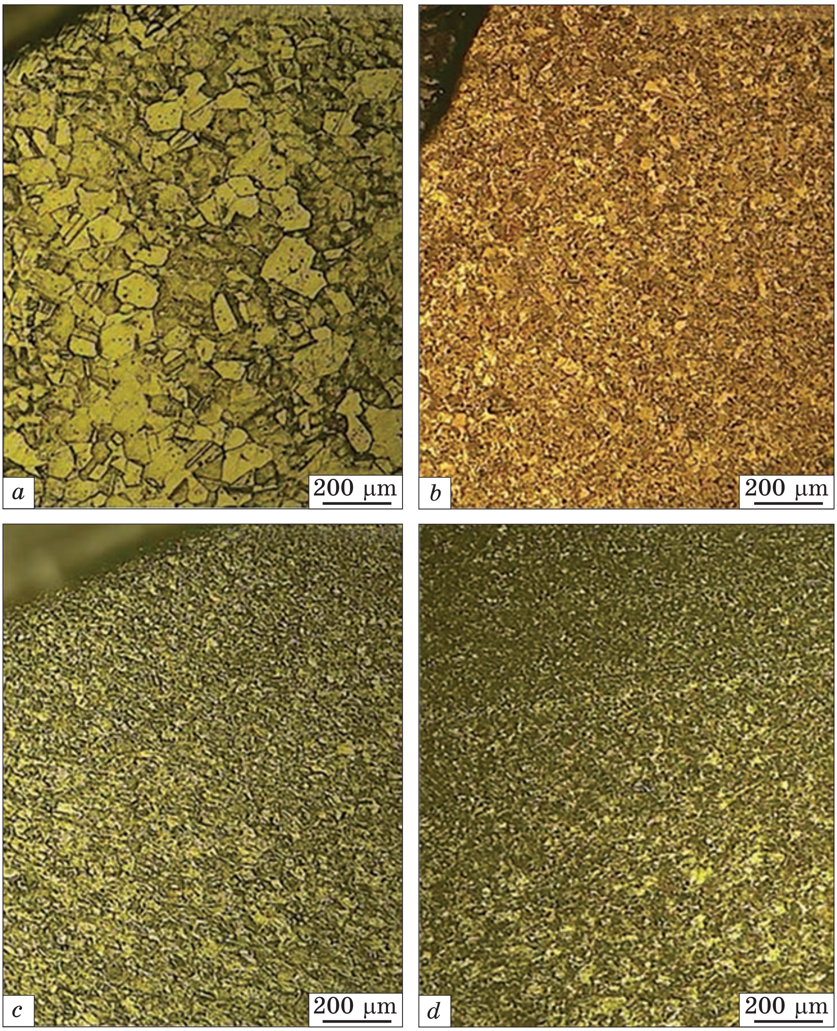


Fig. 17. Microstructure of copper wire after three deformation cycles [56]

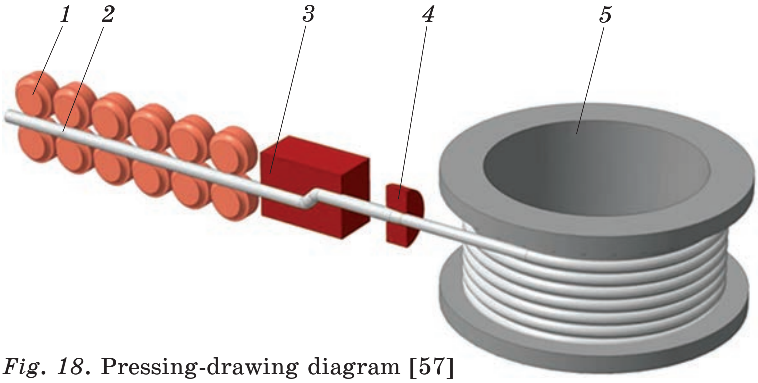


Fig. 18. Pressing-drawing diagram [57]

Additionally, a new method of wire deformation called 'pressing and drawing' is presented in Ref. [57]. This method has proven to be more effective than previously known methods of producing metal with an ultrafine-grained structure (Fig. 18). Using the example of commercially pure copper subjected to deformation under the pressing and drawing process, it was demonstrated that combination of equal-channel angular pressing (ECAP) technology and traditional drawing leads to the formation of a structure with fine, uniform and equiaxed grain, which is characterized by the predominance of high-angle boundaries.

The key to achieving these results was the use of shear deformations occurring in an equal-channel matrix. These deformations provide the formation of a microstructure that is significantly different from that created by standard methods. Importantly, fine-grained structure not only improves the mechanical properties of material, such as strength and ductility, but can also contribute to increased corrosion resistance, which is critical for many industrial applications.

The use of new deformation technologies such as press-draw opens up new horizons for the development of high-strength and lightweight materials that can be used in a variety of industries, including aviation, automotive, and construction. These materials can provide higher efficiency and durability of structures, which in turn can lead to lower maintenance and repair costs. Thus, research into the microstructure and mechanical properties of metals continues to be relevant and necessary for further progress in materials science.

9. Cross-Helical Rolling Processes

One of the promising processes that allows obtaining a gradient microstructure in rods is cross-helical rolling (CHR) and, as one of the varieties, radial-shear rolling (RSR), patented in the work [58]. Its difference from cross-helical rolling is the rolling of a solid rod using a three-roll scheme with large feed angles. Unlike known processes such as equal-channel an-

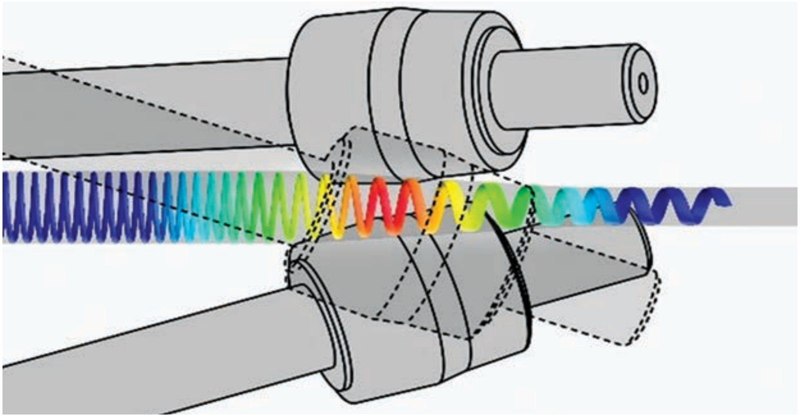


Fig. 19. Pressing-drawing diagram [59]

gular pressing, deformation on a Bridgman's anvil, RSR has a few advantages, particularly, lower values of deformation force, no restrictions on the length of the final workpiece, as well as the possibility of rolling with significant elongation coefficients without destruction.

Radial-shear rolling differs from other metal forming methods in that it not only ensures the final product's high quality, but also allows for significantly reducing the costs of its production. A characteristic spiral macrostructure is formed in the process of radial-shear rolling, which is explained by specific force and kinematic conditions arising from the impact of the technological tool on the workpiece. This leads to the fact that trajectories of various metal layers' movement, having different pitch and angle of helical lines, demonstrate complex patterns. As a result, in addition to the general grinding of material structure, a layer-by-layer orientation of the ground structure occurs, where each layer receives its unique trajectory of movement, which in turn affects the mechanical properties of the resulting product.

During the RSR process in the deformation zone, a stress state pattern close to all-round compression with large shear deformations is realized. In the outer layer, each small trajectory-oriented element is subjected to compression deformation along the radius (diameter) of the workpiece, deformation in the direction of movement and, accordingly, tensile deformation across the helical trajectory (Fig. 19). The elements of the metal structure acquire the form of high-dispersion isotropic, isolated from each other particles. Tendency to form structural banding and meshing, caused by the general drawing of the workpiece, is thus suppressed. Such conditions for metal deformation are not present in any of the known stationary processes for producing rods. In general, over the workpiece volume, helicoidal outflow of metal in the calibre along specified trajectories with deceleration of surface layers and acceleration of central ones creates the

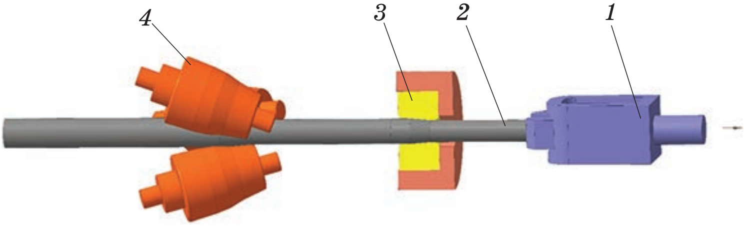


Fig. 20. Broaching and drawing process diagram [61]

effect of a volumetric macroshear. Macroshear deformations are maximally favourable for defect-free plastic deformation of metal and at the same time contribute to a significant increase in the technological deformability of workpieces [59].

However, this method can only deform rods of limited length; for deforming long rods, as noted by the authors of the work [60], very expensive planetary cages are used in RSR.

As an alternative solution for improving of metal deformation process, an innovative combination of radial-shear broaching and traditional drawing was proposed in Ref. [61]. This technology is a unique combination that allows for a significant increase in the efficiency of metal processing. The process begins with broaching the rod through conical rolls that are positioned at an angle of 120° to each other (Fig. 20). This specific configuration provides for simultaneous action on the workpiece in the form of stretching, compression and twisting. Such a complex action leads to a uniform distribution of deformation throughout the entire volume of material, which, in turn, helps to improve the homogeneity of structure. This is especially important for obtaining high-quality metal products with specified properties.

In addition, a combination of radial-shear broaching and drawing allows for a significant reduction in overall processing time. This is because both processes, namely, deformation and rod profile formation, are carried out simultaneously. This approach not only speeds up the production process but also reduces energy and material costs.

During the simultaneous broaching of the rod through the rollers and die, tensile stresses arise, which, as studies have shown, reduce the force required for drawing. This reduction in force is due to the formation of helical dips on the rod surface after the radial-shear broaching stage. These dips, in turn, do not come into contact with the die at the drawing stage, which allows overall force reduction by 15–17%. Significant reduction in force not only facilitates the process but also increases the service life of equipment.

Deformation of the rod is carried out using a gripping device, which carefully and efficiently ensures the rod passes through both deformation tools. In the gap between these tools, the rod is twisted, which further improves the final product's mechanical properties.

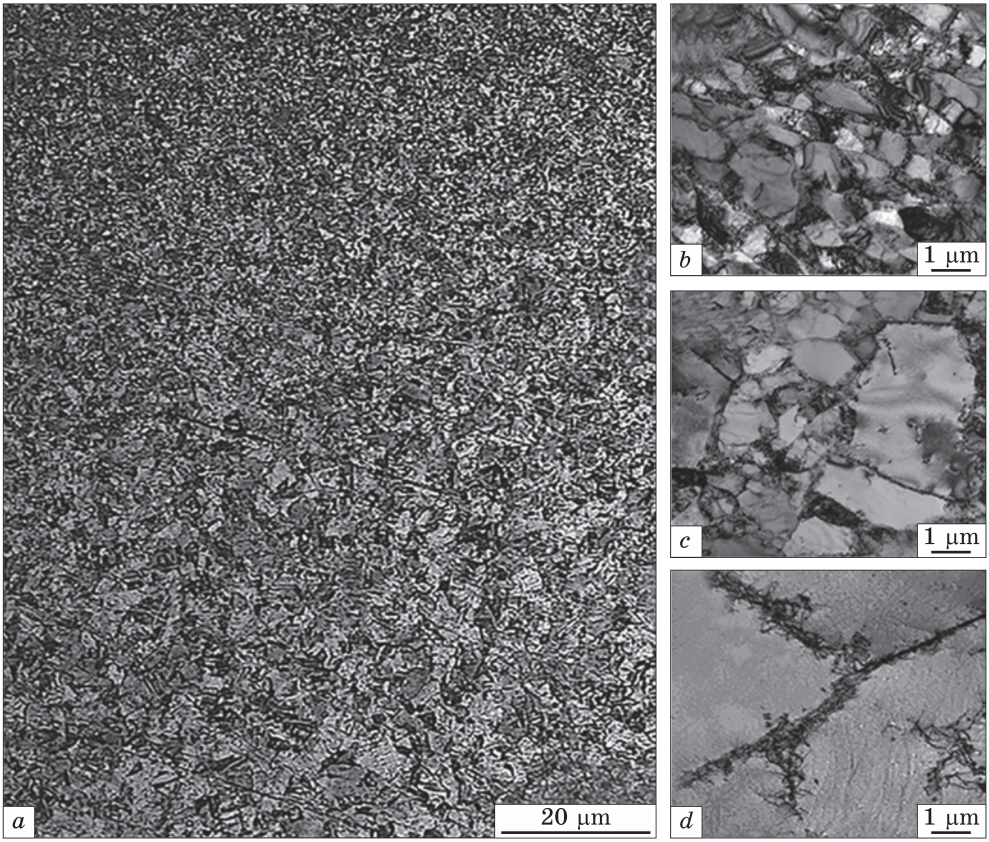


Fig. 21. Microstructure of the rod after deformation [61]

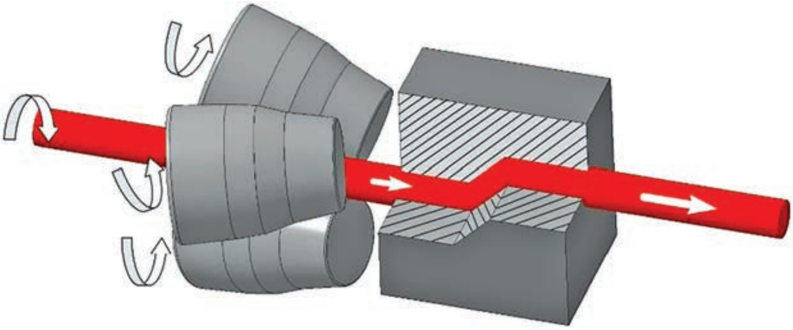


Fig. 22. Schematic diagram of the 'cross-screw rolling–ECA–pressing' process [62]

As a result of such deformation, a gradient microstructure with improved mechanical properties is formed in the rod (Fig. 21).

Thus, the proposed solution combines the advantages of both radial-shear drawing and traditional drawing, which allows optimizing of metal treatment process, improving product quality and reducing costs. Introduction of this technology can lead to significant changes in the metallurgical industry, opening new horizons for the realisation of high-quality metal products.

Combining the process of cross-helical rolling and subsequent pressing in an angular equal-channel matrix allows for to implementation of a stress–strain state scheme with an intensive shear of metal surface layers during screw rolling in the first deformation zone and combining intensive shear deformation of angular pressing with torsion in the second deformation zone. In this case, the central part of the workpiece, which is not processed in the first deformation zone, will receive intensive processing according to a different scheme in the second zone — in a stepped ECA-matrix. This creates good conditions for the formation of an ultrafine-grained structure throughout the volume of a round workpiece. In addition, it is of particular interest to study the parameters of angular pressing with torsion. In essence, we get a process of continuous pressing with elements of workpiece torsion inside the matrix, which will increase the level of accumulated deformation in the volume of the workpiece and will contribute to the processing of the central zone. In the same way as in the method of Ref. [62], more uniform and intense shear deformation during ECA-pressing is superimposed on the less uniform deformation by torsion, which smooths out the non-uniformity that arises after torsion.

Thus, this method, of all the described methods above, is one of the most energy-efficient. Here, unlike 'rolling–pressing', the rolling stand serves not only to push the rod into the matrix, but mainly performs preliminary intensive deformation of the workpiece to a state close to UFG, and the ECA-matrix mainly aligns the structure along the workpiece cross-section. This allows achieving high degrees of deformation in one pass, which is the main factor in energy saving.

Device and process are shown in Fig. 22. Three-high cross-helical rolling mill, characterized by the fact that three conical rolls rotating in the same direction are located in the frame corresponding to the vertices of an equilateral triangle, and their axes are located at an angle to each other and to the rolling axis, is combined with a pressing matrix at the outlet. The matrix has three channels of the same cross-section, two of which (inlet and outlet) are parallel to each other, and the middle channel is located at an angle to the inlet and outlet channels.

There are also experimental studies [63–65], which show that during rolling, the possibilities of additional impact on the deformation centre, in addition form the control effects of this impact on the quality of rolled products and their realization.

10. Conclusions

Existing industrial metal forming methods, as well as high-temperature treatment processes, do not allow for actively influencing the level of traditional structural materials' mechanical properties. Cold working processes used for mass production of high-strength products, such as rolling and drawing, actively strengthen metal materials; however, they have a few limitations associated with the deformation capacity of materials. Therefore, the development of new processes for obtaining high-strength materials is relevant and promising for the accelerated development of production. Processes of plastic structure formation, allowing the formation of a finely dispersed structure in structural materials, leading to a noticeable increase in their strength, wear resistance, fatigue resistance, *etc*., are of particular interest in the scientific world. In this regard, the scientific direction of creating a structure with a grain size of less than one micron in UFG steels is actively developing. Moreover, structure is most effectively refined to UFG and even nanostructured states by SPD, mainly implementing the simple shear scheme under conditions of multicycle processing with a total degree of accumulated deformation of more than 3. Obtaining this type of structure allows for increasing the metallic materials' strength characteristics several times; however, despite numerous developments, modern SPD methods have a few significant limitations, primarily in the aspect of continuity and productivity of process schemes [66–75]. Therefore, searching for the formation of UFG structure in metals, highly productive schemes based on traditional metal pressing processes, is an important stage in the further development of SPD processes. For example, rolling and drawing methods, due to the quasi-monotonic nature of material flow, do not provide effective formation of materials' UFG structure, but have high productivity. Therefore, it remains an important task to improve rolling and drawing schemes to obtain new metallic materials and new types of products.

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ПРОГРЕС У ТЕХНОЛОГІЯХ ПРОКАТНИХ СТАНІВ

Є значна кількість методів фізико-хемічного впливу на металеві матеріали в процесах кристалізації, деформації, термічного оброблення, що спричиняють подрібнення структури. Проте традиційні технології виробництва металевих матеріалів забезпечують грубозернисту будову, оскільки в більшості з них використовуються температури оброблення, за яких дрібні зерна, що виникають, є нестабільними. З точки зору інтенсивної пластичної деформації традиційне вальцювання має істотний недолік, що обмежує його застосування для одержання ультрадрібнозернистої структури в матеріалі. Так, сумарну накопичену деформацію обмежено за звичайного вальцювання багаторазовим зменшенням товщини вальцьованої заготівки. У зв'язку з цим останніми роками було запропоновано низку спеціалізованих способів вальцювання, що уможливлюють усунення цього недоліку.

Ключові слова: вальцювання, інтенсивна пластична деформація, ультрадрібнозерниста структура, мікроструктура.