



Development of Asymmetric Rolling as a Severe Plastic Deformation Method: A Review

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Received: 15 August 2022; Accepted: 11 September 2022

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ABSTRACT

This paper presents an overview of the latest trends in the development of severe plastic deformation (SPD) using rolling methods. From many scientific works, it is known that severe plastic deformation provides intense grain grinding up to ultrafine and nanosized grains during multi-cycle deformation. It is also possible to obtain a uniform or gradient grain distribution over the cross-section of the workpiece. During SPD processes, the strength parameters can be increased several times. Of all the methods considered, asymmetric rolling has become the most widespread owing to its simple implementation in production conditions. Most of the known methods and devices for asymmetric rolling are designed for deformation in rolls with a smooth barrel, while the use of rolls with a relief surface allows the processing of metal to obtain a higher level of equivalent strain. Ensuring a high asymmetry level when rolling in relief rolls allows, in addition to the development of shear strain in two transverse directions (height and width), it also provides an additional level of shear strain in the longitudinal direction. In addition to the speed asymmetry, the rolling scheme in relief rolls is also suitable for the implementation of geometric asymmetry when one of the relief rolls has a reduced or increased diameter while maintaining the relief geometry on the roll surface.

Keywords: Severe plastic deformation, Ultrafine-grained structure, Asymmetric rolling, Sheet workpiece, Speed asymmetry.

1. Introduction: Classical Methods of Severe Plastic Deformation

Currently, there are various methods for obtaining ultrafine-grained (UFG) materials and nanomaterials. The most well-known methods include rapid cooling from the melt, crystallization from the amorphous state, electrodeposition, compaction of nanopowders, and severe plastic deformation. All methods of UFG and nanostructure formation in metals and alloys can be divided into two types: “bottom-up” and “top-down” [1]. The first approach consists of the piecemeal assembly of the material, for example,

by compacting the nanopowders obtained by ball grinding. The second approach is to use special methods of large plastic deformation of bulk blanks, which allow the grinding of grains to the submicrocrystalline range. Such deformation methods for obtaining bulk nanomaterials are called severe plastic deformation methods. In the work of A.M. Glezer, the term megaplastic deformation was proposed [2].

The most developed deformation methods include high-pressure torsion (HPT) and equal-channel angular compression (ECAP) [3-6]. High-pressure torsion was first used to process

metal materials by Bridgman in 1935. The method received its rebirth thanks to the work in the 70-90s of the last century, where it was used to obtain nanostructured states of many pure metals, alloys, intermetallics, and ceramics. When the tool rotates, the sample is deformed by a simple shift owing to surface friction forces. As a rule, the HPT method processes a thin disk with a thickness of approximately 1.0 mm and diameter of up to 20-30 mm [4]. Simultaneously, in addition to torsion, it undergoes precipitation and radial extrusion caused by an applied pressure of several GPa. Using the HPT method in dozens of laboratories around the world, it was possible to obtain nanostructures in a large number of materials, study their features, and evaluate their mechanical and physical properties. HPT is characterized by large gradients of strain and rotation velocity tensors, which cause strong torsion of the radial fibers of the sample. However, the prospects for the use of HPT as an industrial method have significant limitations, primarily owing to the small size of the workpieces being processed and the low durability of the tool owing to the extremely high loads on it.

Equal-channel angular pressing was developed by Segal and his collaborators and was patented in 1973. At the beginning of the 90s of the last century, R.Z. Valiev and his co-authors developed this method and for the first time applied it as a SPD method for obtaining UFG and nanostructures. The principle of this method is to implement a simple shift scheme in the intersection zone of channels of equal cross-section, made in a matrix and located at an angle to each other, when pushing the workpiece through them. ECAP makes it possible to obtain semi-finished products from various elongated materials with rectangular or square cross sections using a relatively simple die tooling design [7]. However, with ECAP, the shape of the workpiece end zone changes because of the peculiarity of the deformation process, which makes it difficult to re-deform to accumulate the necessary deformation degree without intermediate machining. In contrast to high-pressure torsion, equal-channel angular pressing allows for sufficiently large samples with a diameter of up to 60 mm and a length of up to 200 mm.

The maximum equivalent strain in one pass at ECAP with a channel intersection angle of 90° was 1.15. During the passage through the channels, the total shear characteristics in the crystal sample can be changed by rotation between individual passages;

thus, the structure formation during deformation directly depends on the ECAP route [8].

In [9], a method of equal-channel multi-angle extrusion was proposed, which allowed the following advantages to be realized: fractional deformation of workpieces by simple shear with specified time intervals between shifts and the possibility of changing the spatial orientation of the shear planes; a different amount of shear strain accumulated during the passing due to varying the number of deforming matrix bushings and the intersection angles of their channels; and the possibility of changing the parameters of the stress state in the upper deformation zones within certain limits by varying the amount of support due to the different number and height of the bushings located below and different intersection angles of their channels. The paper [10] presents a scheme for ECAP with material flow from a vertical channel into two lateral output channels. This process is known as equal-channel T-shaped pressing.

When implementing the combined ECAP-Conform process, the same idea is used to create a friction force that ensures pushing of the workpiece, as in the case of the traditional Conform process [11-12]. Simultaneously, in the ECAP-Conform process, it is possible to repeatedly push the workpiece through the tool. A chute exists between the rotating central shaft and the stationary matrix, into which the workpiece is loaded. Friction forces arise between the workpiece and shaft during its rotation, causing the workpiece to move after the rotating shaft. The fixed matrix directs the workpiece into a horizontal channel, where the workpiece material undergoes shear strain, as in the typical ECAP process. The ECAP-Conform process makes it possible to obtain long-length products—rods with a relatively small diameter (<10 mm) and an increased length-to-diameter ratio (>5).

The basis of the “Screw extrusion” process is the combination of extrusion processes and SPD by torsion [13]. Screw extrusion is performed in rectangular channels, while the middle part of the channel section is formed by rotating the cross-section of the channel relative to its longitudinal axis, ensuring the rotation of each section of the workpiece when passing through the channel, which is similar to torsion under high pressure, but makes it possible to process large blanks. The limitation of this case is the length of the workpiece being processed.

Comprehensive isothermal forging is one of the

primary and effective nanostructuring methods for massive workpieces [14-15]. The principle of this method consists of repeated deformation of a cylindrical or rectangular workpiece with a change in the loading axis at each transition. At the same time, the grinding of the structure of the processed material is achieved not only by accumulating its changes with the strain accumulation, but also due to the fact that the principle of gradual reduction of grain size is used with a gradual decrease in the deformation temperature. Comprehensive isothermal forging makes it possible to obtain UFG and nanostructures in massive workpieces made of titanium and its alloys, steels, nickel alloys, and intermetallics. The undeniable advantages of this process are its simplicity and the absence of the need to use a special expensive tool. Additionally, this process is easy to automate. However, there is one insurmountable drawback, which limits the single deformation degree owing to the loss of stability of the workpiece during precipitation. In addition, the sediment is characterized by zonal heterogeneity of the deformation of the workpiece, leading to the heterogeneity of its deformation structure. Elimination of the latter requires a large number of cycles and processing steps.

All the above-mentioned deformation methods of nanostructuring belong to discrete SPD schemes, except for the ECAP-Conform process, which is semicontinuous. A discrete scheme of severe plastic deformation is a multi-stage low-productivity process in which intensive plastic deformation of a workpiece of a relatively short length is carried out, that is, there are fundamental structural and technological limitations of the deformation scheme to the length of the workpiece being processed.

Despite the variety of SPD methods, the creation of deformation nanostructuring technologies for industrial use and, in particular, for the production of mass products, including sheet products, is a complex scientific and technical problem, the solution of which requires the development of continuous SPD schemes that ensure the production of UFG and nanostructures in long-length metal semi-finished products. Such new technologies can be based on the well-known metal forming process of rolling.

2. Severe Plastic Deformation Methods of Rolling Type

In recent years, SPD methods have received new impetus for development. This has resulted in the

development of new methods that ensure large plastic deformations in long-dimensional bulk and flat workpieces. Radial-shear rolling can be used to obtain long semi-finished products with significant changes in microstructure and mechanical properties [16-17]. Radial-shear rolling is defined as a special case of stationary screw rolling in the area of large feed angles (16-18° or more) in rolls with special calibration for hot deformation of continuous workpieces of constant cross section [18]. The main purpose of RSR is to produce round, long products, bars, and blanks. Rolling at large feed angles compacts the metal over the entire cross-section. Opening of the cavity was excluded even with a compression of 25%.

The helicoidal metal flow in the deformation zone along specified trajectories with the deceleration of the outer layers of the workpiece and the acceleration of the inner layers creates the effect of volumetric macro-displacement. The metal was deeply compacted and processed at all levels of metallographic structure. The elements of the structural structure of the metal take the form of isotropic isolated particles with high dispersion and a complex increase and stabilization of the physical, mechanical, and service properties of the metal. These features have been described in detail in [19-20].

It has been shown in [21-22] that the high intensity of the shear strain characteristic of screw rolling and the combined "screw rolling-pressing" process makes it possible to significantly grind grains.

The accumulative roll bonding process is based on the following principle: two sheets of the same thickness are subjected to joint rolling with a compression of 50% in one pass [23-26]. The resulting sheet was cut into two sheets, which were folded together and rolled again after the surface treatment. This process is repeated several times. As a result of such combined rolling, owing to the diffusion interaction in the solid phase, the sheets are joined together, accompanied by grinding of the microstructure. This method ensures the production of defect-free sheet semi-finished products with UFG structures.

Cross-ARB process (CARB) is a rolling method similar to the ARB process, but with the difference that after each deformation cycle, the rolling direction changes by 90° [27-28]. This method reduces the plastic anisotropy of sheets and provides a higher level of strength and plastic properties.

Because modern industrial thin-sheet cold rolling mills have a roll barrel length of up to ~2500 mm, the main limitation of the CARB process is the inability to process sheets that are longer than the roll barrel length. In general, the main difficulty in implementing ARB and CARB processes is the need for special surface preparation of the sheets to be joined, as well as cutting the side edges, which reduces the manufacturability of these processes.

Rolling at cryogenic temperatures has high potential for the production of metal UFG and nanomaterials with improved mechanical properties [29-32]. Cryorolling is a method of deformation in which the initial workpiece is pre-cooled, for example, in liquid nitrogen, to a temperature of -153 to...-196°C. At cryogenic temperatures, dynamic return is suppressed, which contributes to more efficient grain grinding. The efficiency of cryorolling as a hardening technology is largely determined by the energy of the packaging defect (EPD) in the processed metal materials. At cryogenic temperatures, metals with low EPD are deformed by the twinning mechanism, with high EPD by the dislocation sliding mechanism, with medium EPD by the twinning mechanism during cryorolling, and by the dislocation sliding mechanism under cold rolling conditions at ambient temperature.

Cryorolling has the potential of application, first of all, for HCC metals, for example, copper, aluminum and their alloys. As a rule, with an increase in the strength of the metals, their plasticity decreases. However, for example, in aluminum alloys with a decrease in temperature from ambient temperature (20°C) to cryogenic (-196°C), the opposite effect occurs; there is a simultaneous increase in both strength and ductility. For example, in the annealed state of alloy 5083, the tensile

strength increased from 290 MPa (at 20°C) to 407 MPa (at -196°C), and the elongation also increased significantly from 25% to 36% [33]. Therefore, cryo-deformation treatment of aluminum alloys can contribute to the formation of UFG structures and increased mechanical properties. For example, in [34], the cryorolling method, in combination with subsequent annealing, was used to obtain a UFG structure in aluminum alloy 5083.

One promising industrially applicable SPD method is asymmetric rolling [35-44]. Rolling is a complex technological process accompanied by disturbances; thus, any rolling process is asymmetric. Symmetric rolling is an idealization of real conditions. However, asymmetry can be created purposefully because of the mismatch of the circumferential speeds of the rolls when using an individual drive, the difference in the diameters of the rolls, and the use of a non-driven (idle) roll, as shown in Fig. 1.

During asymmetric thin-sheet rolling, additional shear strains occur, which, in combination with compression deformations, can ensure effective structural grinding of the processed metal materials, as shown in Fig. 2. In the following chapters of the monograph, the theory of this process as a method of SPD is discussed in detail.

Large shear strains created in the process of asymmetric rolling, as well as suppression of dynamic return and activation of mechanical twinning at cryogenic temperatures, can be combined in one process, asymmetric cryorolling, as shown in Fig. 3.

A number of foreign works have successfully applied asymmetric cryorolling to produce aluminum and its alloys 6061, 5052, and 5083 with an ultrafine-grained structure and enhanced mechanical properties [45-47]. The authors of these

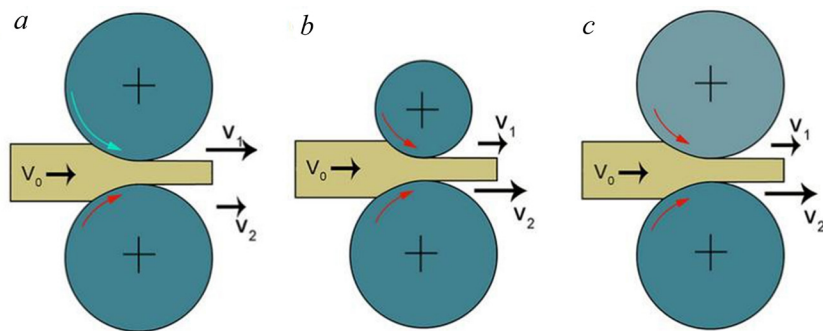


Fig. 1- Variants of asymmetric rolling: a – in rolls of different circumferential speeds; b – in rolls of different diameters; c – with one non-drive roll [44].

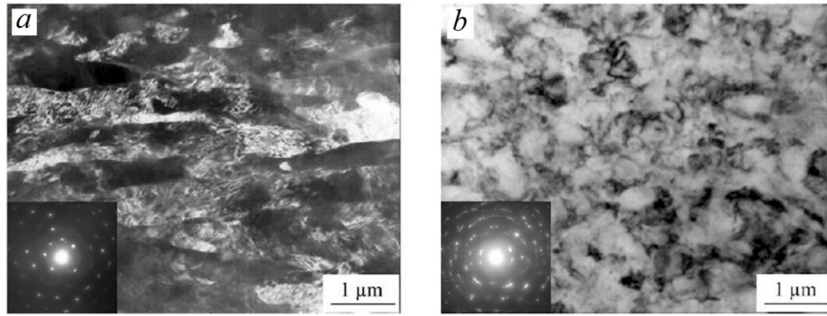


Fig. 2- Microstructure of aluminum alloy 5052 after symmetric (a) and asymmetric (b) rolling [44].

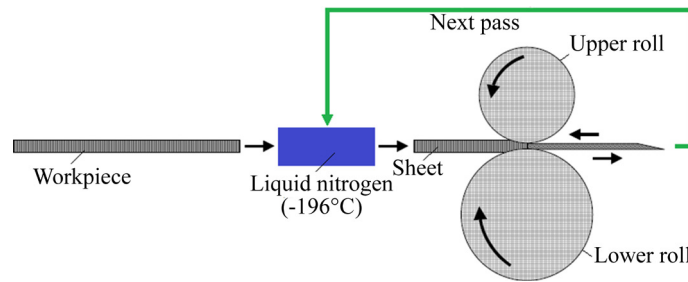


Fig. 3- Scheme of the asymmetric cryorolling [44].

works achieved the smallest grain size (~211 nm) with asymmetric cryorolling of pure aluminum in comparison with SPD methods, such as ECAP, ARB, screw extrusion, or asymmetric rolling at ambient temperature, as shown in Fig. 4.

Among all the methods considered, asymmetric rolling has become the most widespread owing to its simple implementation under production conditions.

3. Methods of Asymmetric Rolling Implementation

The growing demand for sheet metal consumers, their quality, and increased competition requires sheet metal manufacturers to search for new technologies and implement them in production. One such process is asymmetric rolling (AR). In the last 15-20 years that extensive research and application of AP has begun, first on cold rolling mills, and then on hot rolling mills. The impetus for this was the commissioning of working stands with an individual roll drive. The practice of research and application of AR processes in the hot and cold rolling of sheets indicates the possibility of controlling at the same time almost the entire spectrum of rolling parameters and service properties of sheets and strips [48].

Asymmetric rolling reduces the rolling force and energy consumption for the deformation process, reduces the longitudinal and transverse

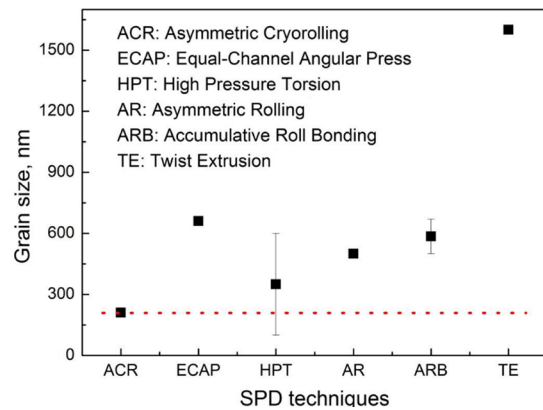


Fig. 4- Minimum grain size of pure aluminum during processing by various SPD methods [46].

thicknesses, improves the flatness and shape of the strip, and enables quick control of the surface quality and physical and mechanical properties of rolled products. An analysis of the factors that affect the broadening and methods of asymmetric rolling has shown that the most rational way to study the effect of roll speed mismatch on the broadening of the leading and driven rolls is speed asymmetry. The use of speed asymmetry makes it possible to directly regulate the mismatch of roll speeds over a wide range during the rolling process and also allows the use of automatic control systems [49].

The division of the rolling processes into

symmetrical and asymmetric processes is arbitrary. If the rolling process has no signs of intentionally introduced asymmetry and the effect of asymmetry on the rolling conditions is insignificant and determined by the tolerances of the technology, then such a rolling process is referred to as symmetrical. If the asymmetry is set by special technological techniques such as the use of working rolls with unequal diameters, rotation of working rolls with different circumferential speeds, and application of different roughness on the roll surface, the rolling process is referred to as asymmetric [50].

The asymmetric rolling process manifests itself in the uncontrolled bending of the strip during its capture by the rolls and on the plane of exit from the deformation zone, in the acceleration of the rolls together with the strip, in the uneven load of the drives, and in the existence of a control and controlled working roll. Consequently, there are disadvantages in the area of the strip shape, undulation, and unevenness of the strip thickness on its width and length, which cannot be removed during further editing operations.

There are different principles for classifying asymmetric rolling processes. Korolev [51] calls rolling asymmetric if the rolls have different circumferential velocities and different coefficients of contact friction from the upper and lower rolls. The difference in the circumferential speeds of the rolls is achieved in practice in three ways: by using rolls of unequal diameter at the same angular speed of rotation; by using one drive roll and the other idle, while the speed of the idle roll is self-adjusting slightly less than the drive; and the use of rolls of the same diameter, forcibly rotating at different angular speeds. This, along with improving the service properties of the finished rolled products, significantly changes the degree of load on the transmission of the leading (having a high speed) and driven rolls. The load on the transmission and drive of the drive roll increases, and the driven roll and drive are unloaded until switching to the generator mode.

Studies on the effect of velocity asymmetry on the energy-power parameters of rolling were carried out under both laboratory and industrial conditions. For laboratory mill 340, the authors of [52] modeled the rolling conditions in the last passes of the finishing stand of mill 3000. Lead samples were used. Experiments showed that the rolling force decreases with an increase in the asymmetry coefficient to 1.20.

The aim of this study [53] was to determine the stress state and velocity parameters during asymmetric strip rolling. To assess the stress state and velocity values in the plastic deformation zone, a theoretical method of sliding lines was used, which has proven to be effective in solving plane and axisymmetric problems. The analysis of the study results showed that compressive stresses act in the plastic deformation zone, contributing to the grinding of the metal structure and the closure of all internal defects. Owing to the roll speed differences, shear strains were created in the longitudinal and transverse directions of the strip, which positively affected the quality of the workpieces. Simultaneously, the occurrence of shear deformation in the longitudinal direction reduces the unidirectional metal flow in the rolling direction. As a result, the mechanical properties of the metal are averaged, which positively affects the quality of the rolled metal products during subsequent cold stamping.

The realization of high shear strain is a determining factor in the development of the asymmetric rolling process as an SPD method. Figure 5, a shows symmetrical rolling, where the shear strains are extremely small and the inclination of the vertical sections does not occur. Figure 5, b shows an asymmetric deformation zone; when only the lag zone is realized in one roll, and only the advance zone on the other, the intensity of shear strain can reach 2-3 more units [54].

A method of strip rolling is known [55], in which the plastic deformation of metal is carried

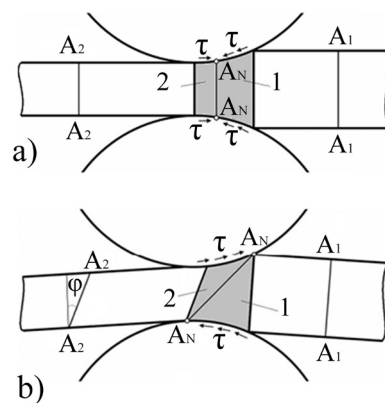


Fig. 5- Simplified scheme of symmetric (a) and asymmetric (b) deformation zones in the extreme case (1 – lag zone; 2 – advance zone; $A_n A_n$ – neutral cross-section; τ – contact friction forces; $A_1 A_1$ – cross-section before deformation; $A_2 A_2$ – cross-section after deformation; ϕ - inclination angle of cross-section) [54].

out in profiled rolls with longitudinal bending of the strip issued from the rolls, as shown in Fig. 6. In this well-known rolling method, the intensification of the plastic deformation process is ensured owing to the constant value of the shear strain between the upper and lower layers of the roll, which in turn is a direct consequence of the constant value of the mismatch of the roll circumferential speeds between the extreme and central fibers along the width of the strip.

In [56], the authors compared shear strain during equal-channel angular pressing, symmetric rolling, and asymmetric rolling. It is shown that with asymmetric thin-sheet rolling with a compression of 60% at the optimal process parameters, the shear angle exceeds 80°, and the true strain in one pass is approximately 3.8...4.8 in sheet thickness.

The tensile residual stresses arising in the sheets after asymmetric rolling can cause nucleation and growth of microcracks, leading to the destruction of the processed material. In [57], based on numerical modeling using the finite element method, an analysis of the residual stress distribution over the strip thickness of aluminum alloy AMg6 after processing by cold asymmetric rolling with mismatch of the circumferential speeds of the working rolls was performed. It is shown that the greatest influence on the formation of residual stresses is exerted by the mismatch degree of the circumferential speeds, as well as the geometric shape of the strip formed simultaneously owing to vertical bending. It was established that the level of residual tensile stress was maximal after asymmetric rolling with $\Delta V=40\%$ and reached 75 MPa, and minimal at $\Delta V=50\%$, not exceeding 14 MPa.

It was shown in [58-59] that asymmetric rolling of metal sheets with a high single degree of deformation ($\epsilon \geq 50\%$), a high coefficient of contact friction ($\mu=0.3-0.4$), and a large mismatch

of roll speeds ($V_1/V_2 \geq 2$), as shown in Fig. 7. This allows the creation of ultra-high shear strains in deformable metals (shear angle $\varphi = 45^\circ-85^\circ$) and provides a high level of true accumulated strain ($e = 4-6$). However, with such process implementation parameters, deformation heating of the metal occurs, which significantly affects the thermal and mechanical conditions of metal deformation. Such heating for aluminum alloys can reach the temperature at which recrystallization begins and even the melting point.

In [60], the authors studied the change in the mechanical properties of low-carbon steel rolled in cone-shaped rolls. The mechanical properties of low-carbon steel after asymmetric rolling are much better than those during symmetrical rolling at different temperatures. It should be noted that with an increase in temperature to 1100°C, the Luders deformation is manifested during asymmetric rolling; conversely, the sample after symmetrical rolling with a decrease in temperature to 900°C shows less Luders deformation. The design of the rolls shown in Fig. 8 is chosen in such a way as to be able to roll samples on conical and cylindrical barrels and compare the results of deformation.

The diameter of the cylindrical part of the rolls was 43.3 mm, which is the average diameter in the average section of the cone part of the roll. The difference in the diameters of the cone part of the roll was 16.7 mm, and the ratio of the larger diameter to the smaller was 1.5.

Asymmetric processes are widely used for the production of sheet metals. In [61], a device for obtaining rolled products was proposed, including at least two sequentially installed rolling stands, in the first cage one roll with a smooth barrel, and the second cage contained two rolls with a smooth barrel, characterized in that in the first cage on the working cylindrical surface of the second roll, there are projections in the form of trapezoidal

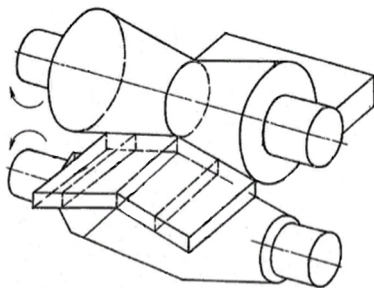


Fig. 6- Rolling scheme in profiled rolls [55].

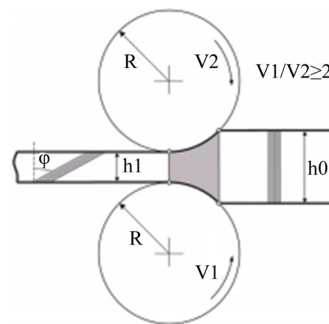


Fig. 7- Scheme of asymmetric rolling with a large mismatch in roll speed [58].

helical lines in the contour, while on one half of the cylindrical surface, the helical line has the right direction, and on the other half, the left direction.

When the metal is deformed in the first cage between a roll with a smooth barrel and a roll with projections in the form of helical lines of a trapezoidal contour, the metal in the deformation zone moves both along the rolling axis and perpendicular to the rolling axis. In this case, the metal moves from the middle plane of the roll to the edges of the roll because on one half of the cylindrical surface, the helical line has the right direction, and on the other half, the left direction. Then, when deforming between cylindrical rolls in the second cage, the metal from the crimped protrusions flows into depressions where there is no compression, and thereby receives transverse deformation. As a result, the unevenness of the hoods along the width of the rolled metal decreased, the flatness increased, and the sickle shape decreased.

In work [62] a device for rolling a strip with a wedge-shaped cross-section, including at least two consistently installed rolling stands, was proposed. The first crate contained an axis with disks impaled on it and a roll with a smooth barrel. The second crate contained two rolls with smooth barrels. The disadvantage of this device is the low rigidity of the axis-disk system. During rolling, under the influence of force from the strip, the axis is deformed, which leads to an additional distortion of the shape of the cross-section of the strip profile, namely, convex, concave, or asymmetric (for example, wedge-shaped), which leads to a decrease in flatness, as well as an additional increase in the sickle shape, which is undesirable. The aim of this model is to increase the flatness and reduce the

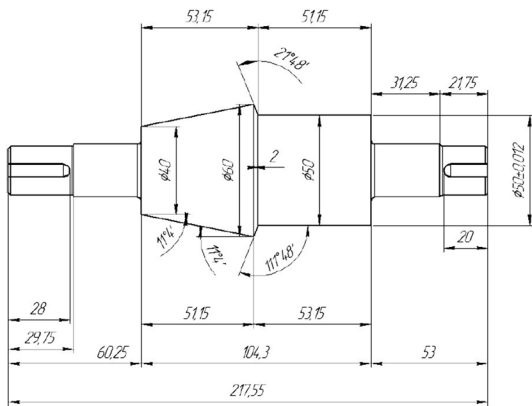


Fig. 8- Working roll with reverse taper of the DUO 50 mill [60].

sickle shape of the rolled products.

In work [63] a rolling device is described, which is designed to improve the quality of rolled products and reduce the loads on the equipment. An increase in the property uniformity along the sheet thickness and a uniform load distribution on the rolls during rolling are ensured because at least one roll set is movable relative to the crate in the rolling direction.

In [64], the authors patented a method for asymmetric rolling of thick-sheet metal, including heating of the workpiece, rolling it in working rolls of different diameters, and plastic bending with a bending roller, characterized by the rolling of the front and rear sections of the workpiece, the length of which is equal to the axial distance between the bending roller and the working rolls, was carried out with a mismatch of the angular velocities of the working rolls in the range of 1.0-20.0%. The method shown in Fig. 9 allows the creation of a strain state in which the elongation of the metal layers along the entire length of the workpiece becomes the same).

For many years, the Magnitogorsk State Technical University has been actively operating a scientific school on the asymmetric rolling of sheets and tapes. In particular, the main feature of asymmetric rolling is the rotation of the deformation zone caused by the moment from the opposite direction of the friction forces in the mixed zone of the deformation zone. A new combined process of vertically asymmetric rolling and bending was proposed [65]. The technology for obtaining large-sized bodies of rotation at a 4500 mill was developed and implemented (a roller of the diverting roller was used as a bending roller) [66].

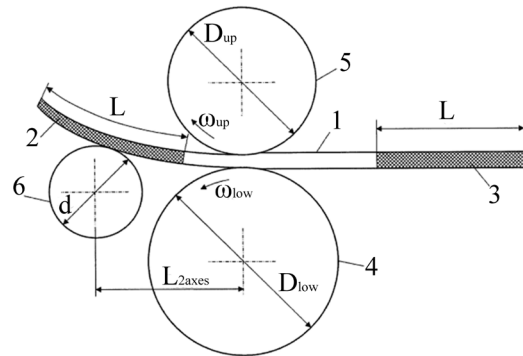


Fig. 9- Method of asymmetric rolling of thick-sheet metal [64].

The authors of [67] proposed a method that includes rolling with a mismatch of the roll speeds in a multiroll caliber formed by at least three rolls. A more complete study of the metal owing to large shear strains, which allows obtaining a finer grain score, is provided because the circumferential speeds of all rolls in the caliber are set with their increase in the direction of clockwise movement in accordance with the ratio $v_1 < v_2 < \dots < v_i < \dots < v_n$. During rolling, the areas of the metal surface in contact with the rolls having a lower speed slow down, owing to which the metal receives less extraction. Areas in contact with rolls have high circumferential speeds, accelerate, and receive large exhaust. In the caliber of the cage, there was an uneven redistribution of hoods along the section of the deformed workpiece. The working rolls (1-4) located in the same plane and forming a four-roll gauge, are shown in Fig. 10.

Workpiece 5 is set in working rolls 1-4, located in the same plane and form a four-roll gauge. When rolling in a multiroll caliber, where the values of the circumferential speeds of the rolls are set to increase in the direction of clockwise movement, a zone of accelerated metal flow is formed at the contact of the metal with roll 4 with the highest speed, and a zone of slow metal flow is formed at the contact with roll 1 with the lowest speed. This leads to the possibility of a more uneven redistribution of the hoods along the cross section of the deformable workpiece and obtaining large shear strains in the metal volume.

4. Asymmetry Factor During Rolling in Relief Rolls

The considered methods of asymmetric rolling are carried out in rolls with smooth barrel – even

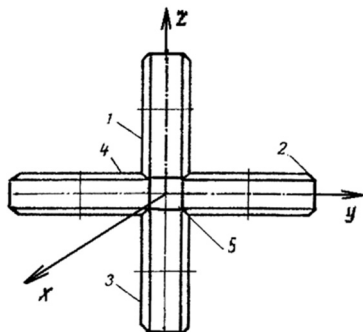


Fig. 10- Working rolls (1-4) located in the same plane and forming a four-roll gauge [67].

cone rolls [60]. Despite their structural complexity, they have a rectilinear deformation surface on which the workpiece is rolled at an angle. A separate category of asymmetric rolling is the rolling method for rolls with different relief surfaces.

In [68], a new design of roughing-cage rolls for sheet rolling mills was proposed. It includes drive horizontal rolls with a profile working surface in the form of annular collars and streams, which are made with equal radii r of their profiles and the ratio of the distance e between the lines of the centers of the semi-cylindrical surfaces of the collars and streams to the radius r equal to $s = e/r = 1,8 \dots 1,9$, as shown in Fig. 11.

In this case, the rolls are installed with a gap a between the ring collars, equal to $a = H - 4\Delta$, and with a gap b between the vertices of the ring streams, equal to $b = H$, where H is the height of the rolled strip, and $\Delta = r - e$ is the height of the circumference sector of the ring stream. The result of using these rolls is an increase in strength and plastic characteristics and an improvement in the deformation processing of the cast metal structure by additional alternating strain under compressive stresses without changing the shape of the cross-section of the workpiece.

In [69], an energy-saving technology for rolling thick-sheet metal was developed, which solved the problem of obtaining high-quality thick-sheet metal without significantly changing the initial dimensions of the workpiece. For this purpose, two new designs of working rolls with relief surfaces in the form of annular ducts forming trapezoidal protrusions and depressions alternating one after another along the entire length of the barrel were designed. Figure 12 (a) shows the “first” scheme, where the rolls with an unequal ratio of protrusion

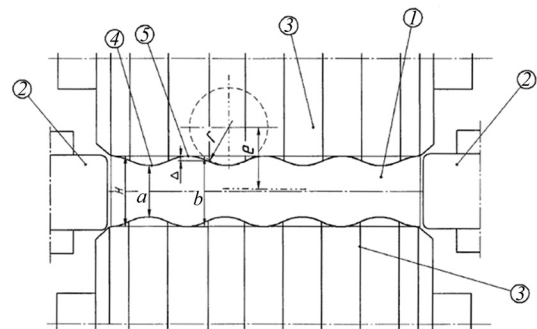


Fig. 11- Roll assembly of the roughing stand of the sheet rolling mill: 1 - blank; 2 - vertical non-drive rolls; 3 - horizontal drive rolls; 4 and 5 - ring collars and streams on a barrel of vertical rolls [68].

to depression. Figure 12, b shows the “second” scheme, where the rolls with an equal ratio of protrusion to depression.

In [70], the advantages of rolling a thick-sheet billet in relief rolls of the proposed design were presented in comparison with smooth rolls, and it was proved that the most optimal design is relief rolls with an unequal ratio of protrusion to depression.

During the surface microstructure study of brass billets rolled according to the current and proposed technologies, it was revealed that the initial grain was ground during deformation. Blanks rolled in smooth rolls have a pronounced grain elongation along the rolling direction and, consequently, property anisotropy in the volume of the deformed metal. The surface analysis of the workpieces rolled in relief rolls with an unequal ratio of protrusion to depression showed that grain elongation was not

detected either in longitudinal or in cross sections. The use of such a tool makes it possible to obtain a fine-grained isotropic structure in the volume of the deformed metal.

Studies conducted using a JEOL JEM2100 transmission electron microscope have shown that the use of both smooth and relief rolls leads to the predominant formation of lines and sliding bands of dislocations in the longitudinal direction. At the same time, the maximum difference in the number of sliding lines when comparing the longitudinal and cross sections was observed after rolling the brass blanks in smooth rolls. In addition, the use of smooth rolls leads to uneven sliding of dislocations because only the most favorably oriented sliding systems are involved. Visually, this is expressed by the fact that there are more dislocation lines inside some grains than in others, as shown in Fig. 13 (a) and (b). After rolling in relief rolls, this is not

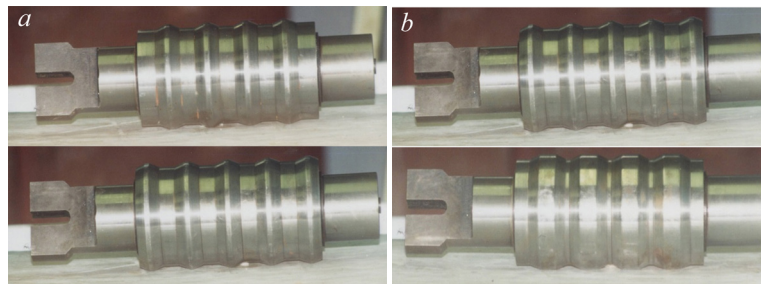


Fig. 12- Relief rolls with an unequal ratio of protrusion to depression (a), with an equal ratio of protrusion to depression (b) [69].

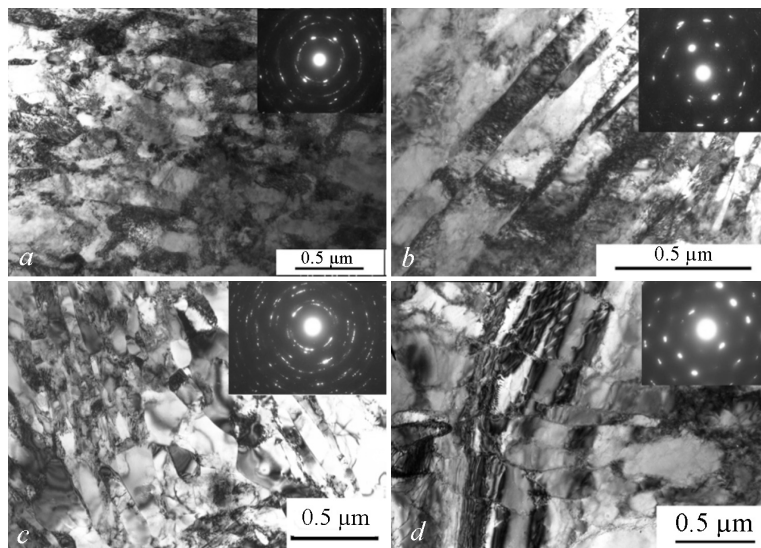


Fig. 13- Microstructure of brass blanks when examined with an transmission electron microscope after rolling in smooth rolls and relief rolls with an unequal ratio of protrusion to depression: a) in smooth rolls, transverse direction; b) in smooth rolls, longitudinal direction; c) in relief rolls, transverse direction; d) in relief rolls, longitudinal direction [69].

observed, the distribution of sliding lines inside individual grains in both directions is uniform, as can be seen in Fig. 13, c, d, i.e. all grains are relatively equally involved in the sliding of dislocations and in plastic deformation.

In [71], the results of research on improving the deformation technology of thick-sheet blanks in relief rolls were presented. Considering that asymmetric rolling allows for an increase in the level of shear strain during rolling, an asymmetry factor was introduced into this technology, as shown in Fig. 14.

Owing to the structural design of the roll profile, a certain level of shear strain in the transverse direction was reported on the workpiece during rolling. Because of the difference in the speed of rotation of the rolls, a state of kinematic asymmetry arises, which leads to the realization of an additional level of shear strain in the longitudinal direction. In aggregate, the implementation of shear alternating strain leads to a significant increase in the processing level of the initial structure and an improvement in the mechanical characteristics at a constant compression level. The asymmetry factor is introduced by the mismatch of the roll circumferential speeds, and the speed of the lower roll is higher than that of the upper roll. This is necessary so that in the case of a possible curvature of the workpiece, it bends upward.

When the asymmetry factor is included in this scheme, a key feature is noted. Despite a sufficiently high asymmetry level, the workpiece did not bend after leaving the deformation zone of the relief rolls, maintaining its horizontal movement trajectory. This effect was achieved because of the resulting relief section of the workpiece, in which the protrusions and depressions formed performed the peculiar role of the stiffeners. Simultaneously, an increase in the asymmetry coefficient leads to an

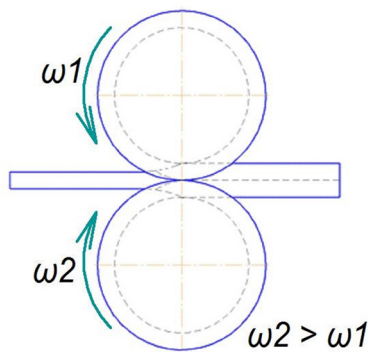


Fig. 14- Scheme of asymmetric relief rolling [71].

increase in the level of the equivalent strain along the entire section of the workpiece. Thus, with an asymmetry coefficient of 1.5, the maximum strain level was 1.4-1.46 at the contact with the annular grooves, in the opposite zones the strain level increased to 0.7. At the same time, there were practically no strain drop zones on the inclined sections, as shown in Fig. 15.

Thus, it was found that the introduction of the asymmetry factor into the rolling stage in relief rolls favorably affected the processing level of the deformable metal. The Lode-Nadai coefficient was used to analyze the stress state. This coefficient allows the assessment of the nature of deformation occurring in the workpiece, that is, to determine which type of deformation is realized at a particular point – stretching, compression, or shear.

The coefficient values varies from -1 to 1. A value from 0 to 1 corresponds to compression, from 0 to -1 corresponds to stretching, and a coefficient value tending to 0 corresponds to shear. The Lode-Nadai coefficient was calculated in three zones:

- on the upper face of the workpiece at the point of contact with the upper roll;
- in the central plane of the workpiece;
- on the lower face of the workpiece at the point of contact with the lower roll.

The results are shown in Fig. 16. The profile of the workpiece obtained during rolling is as follows. In the central zone, mainly compressive stresses develop, the maximum values of which occur in

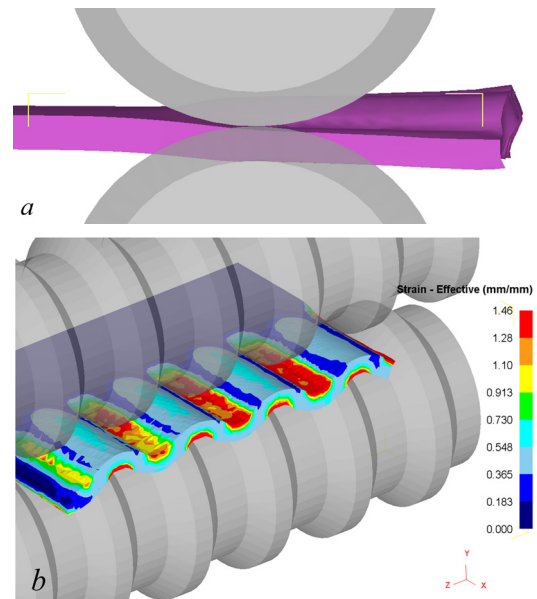


Fig. 15- Common view of rolling (a) and equivalent strain distribution in relief rolls with an asymmetry coefficient of 1.5 (b) [71].

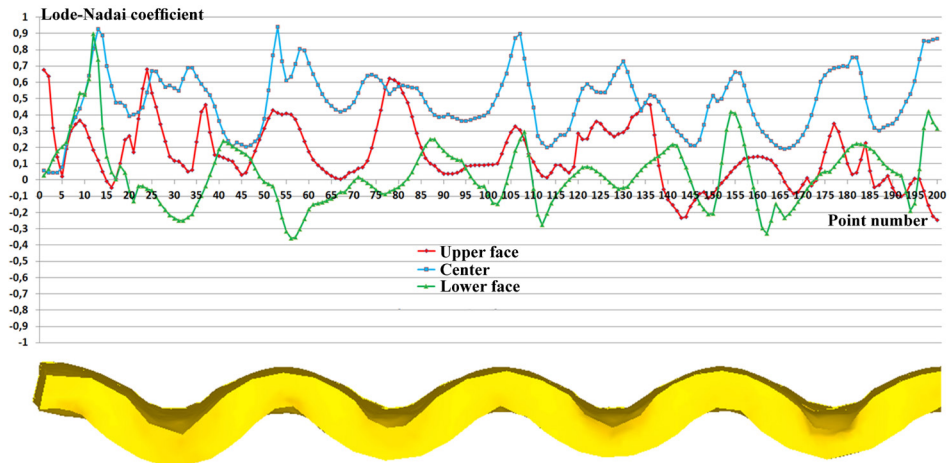


Fig. 16- Lode-Nadai coefficient [71].

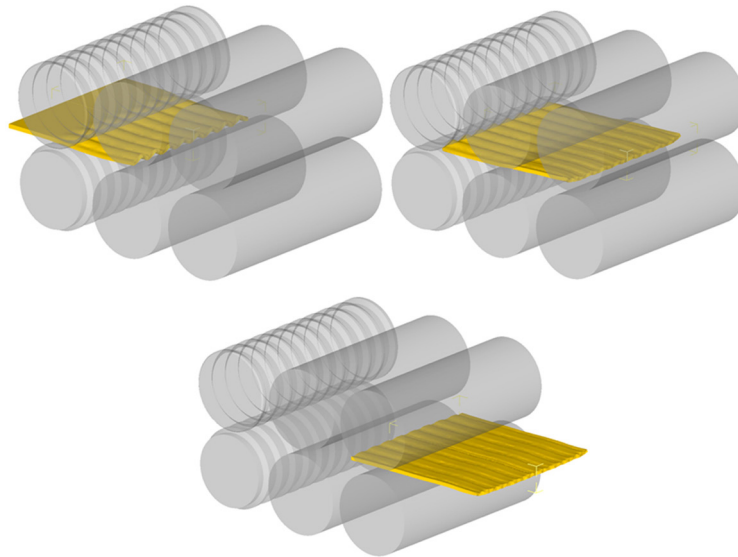


Fig. 17- Model of 3-pass rolling.

the regions of the ridges, where the value of the Lode-Nadai coefficient is 0.7-0.9, In inclined areas due to the action of shear strains, the compression level decreases, and the value of the Lode-Nadai coefficient is 0.2-0.4. The surface zones have a similar stress distribution compared to the central one – here compressive stresses develop in the ridge zones, which are significantly lower than in the central one - here the value of the Lode-Nadai coefficient is 0.4-0.6 on the upper face and 0.2-0.3 on the lower one. In inclined sections, the value of the Lode-Nadai coefficient tends to zero, which indicates the intensification of the shear strain in these areas. Comparing both surface zones, it can be noted that even small stretching zones appear on the lower face, where the value of the Lode-Nadai coefficient is 0.2-0.35.

Because the implementation of asymmetric rolling in relief rolls leads to the exit of the strip from the rolls almost without bending, this effect makes it possible to introduce this deformation technology into the continuous rolling scheme. For this purpose, a 3-pass rolling was modeled, where in the first pass, the workpiece was subjected to asymmetric rolling in relief rolls, and in the second and third passes, it was straightened. It is established that the deformation according to this scheme occurs stably without jamming the workpiece (Fig. 17). This scheme of asymmetric rolling in relief rolls is the most promising for implementation in existing rolling mills. Moreover, relief rollers with different diameters can also be used to achieve a high level of asymmetry.

5. Conclusions

Traditional methods of severe plastic deformation have proven themselves well in terms of intensive grinding of grains to ultrafine and nanoscale levels. However, they are unsuitable for industrial use and mass production owing to the impossibility of processing long blanks and ensuring continuous deformation. These problems can be solved using a rolling process.

Well-known rolling methods that implement severe plastic deformation allow for the production of high-quality long-length blanks in the form of rods or sheets. However, most of these technologies require either special mill designs (radial-shear rolling) or the introduction of additional operations for processing the workpiece (surface treatment and cryogenic cooling).

Various asymmetric rolling methods allow for a high strain level, which leads to significant grain grinding. Methods of both speed asymmetry (with a difference in the rotation speed of the rolls) and geometric asymmetry (with a difference in the diameters of the rolls) are being actively developed.

Rolling in relief rolls is an asymmetric rolling process with uneven metal processing, both in terms of the thickness and width of the workpiece. However, the introduction of an additional speed asymmetry factor led to a significant increase in processing level. At the same time, the presence of a relief section of the workpiece, in which the formed protrusions and depressions act as stiffeners, leads to the fact that after leaving the deformation zone of the relief rolls, the workpiece practically does not bend, maintaining its horizontal movement trajectory. This effect makes it possible to introduce asymmetric rolling in relief rolls into a continuous-rolling scheme.

Acknowledgements

This research was funded by the Science Committee of the Ministry of education and science of the Republic of Kazakhstan (Grant № AP14869080).

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