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# Obtaining long products by severe plastic deformation methods: A Review

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**ABSTRACT**

Over the last 20-30 years, severe plastic deformation (SPD) technologies have caused a significant resonance in the production of ultrafine grained and nanostructured materials. However, the growth of demand for such technologies is largely limited by the high cost of making products from such materials due to the high energy and labour intensity of their production. Therefore, this article analyzes modern technologies for the production of ultra-fine grained metals and alloys with high strength and ductility, using relatively simple and inexpensive equipment and with minimal time required for their production. The development and proliferation of continuous casting machines in the second half of the 20th century led to the development of many continuous press methods used for deformation of long billets, among which Conform, Extrolling, Linex and combined rolling-press technologies stand out. Therefore, in the present article all combined and continuous processes currently available for the production of long products with ultrafine grains and nanostructures will be considered. Such structures are fundamentally different from conventional materials, because they combine high strength properties with high ductility. This is relevant for applications where weight, size or special performance characteristics of the parts are important.

***Keywords**: Severe plastic deformation, Long strips, Wire, Long billet, Method.*

## 1. Introduction

Today in many industries there is an intensive development of research in the field of "nanotechnology". In metallurgical production it is a reaction to the state close to the exhaustion of possibilities to create the required properties in alloys by traditional methods. Minimizing the grain is the way to the possible abolition of all metal forming processes in general. Reducing the size of the particles that make up an object gives it new properties in general. This is caused: first, by the influence of developed boundaries, since the boundary conditions are different from the intra-grain conditions; and second, by the absence of conditions within the grain that manifest themselves in a large volume. Therefore, nanosize grains are capable of imparting substantially new qualities to the same alloy while maintaining the chemical composition.

Fabrication of metal nanomaterials in the form of billets of a volume sufficient for the manufacture of products can be accomplished in three ways: by compacting powders with nanoscale particles, by severe plastic deformation, and by special casting methods. The most attractive way to produce bulk nanocrystalline materials is severe plastic deformation (SPD), which consists in repeated deformation of the processed materials under conditions close to simple shear. The main methods by which large deformations leading to appreciable grain refinement are achieved without destroying the sample are surface ironing with a solid indenter, high pressure torsion, equal channel angular pressing, all-round forging, “helical” pressing, etc. On the one hand, the above methods of severe plastic deformation make it possible, along with a reduction of the average grain size, to obtain massive samples with a virtually porous structure, which cannot be achieved by compacting highly dispersed powders. On the other hand, their main disadvantage is low productivity, which hinders the industrial production of products with the properties inherent to nanostructure. Therefore, in recent years, highly efficient methods of obtaining ultrafine grained (UFG) materials based on rolling and pressing processes have become widely used.

## 2. Analysis of ways of receiving lengthy preparations by SPD methods

The use of methods of severe plastic deformation, such as high pressure torsion (HPT) [1,2], equal-channel angular pressing (ECAP) [3-5], screw extrusion leads to the grinding of the alloy structure, but they are not applicable for obtaining long ultra-fine-grained blanks. The result of approximation of SPD processes to the conditions of industrial production is continuous SPD methods.

The Conform method (Fig. 1) [6] is a type of continuous pressing that was developed in 1971 in England. The principle of processing materials according to the Conform scheme is shown in fig. 1. The Conform is based on continuous deformation of the workpiece by feeding it by active friction forces into the working channel formed by the shoe and a movable rotating wheel with a stream in the form of a groove along the periphery, while a matrix is installed at the end of the shoe, which forms a decompression chamber.

It is worth noting that the traditional Conform method is characterized by high energy intensity and increased unevenness of deformation. A new direction of development of the method was its development as a method of severe plastic deformation for obtaining long products with ultra-fine-grained structure.

In recent years, a large number of Conform-type schemes have been developed.

Using a single rotating disk as the driving force of the extrusion process allows you to produce products of unlimited length. The disk of the simplest design has a peripheral recess, through which the incoming raw material is transferred to the crimping.

The chamber where the working material is located is supported by a pad. The chamber also contains a protrusion that contacts the disk groove. The force of the rotating disk causes the raw material located near the ledge to flow into the chamber, from where it is then displaced. In addition to the commonly used rods, materials of any morphology can be used as raw materials, provided that the dimensions correspond to the size of the groove (Fig. 2) [7].

The new Conform machines of “i” series from BWE use a patented induction heating system that provides efficient direct heating of the displacement zones. The ability to quickly preheat the chamber to the desired level of displacement temperature before directly starting the machine reduces the load on the tool part and allows you to work with more complex products for displacement. The Conform process is used to produce a wide range of non-ferrous metal products, including aluminum and copper alloys, zinc, calcium, lead, and magnesium.

The Conklad process geometry is designed so that the core of the material falls into the displacement zone. To ensure the flow of metal

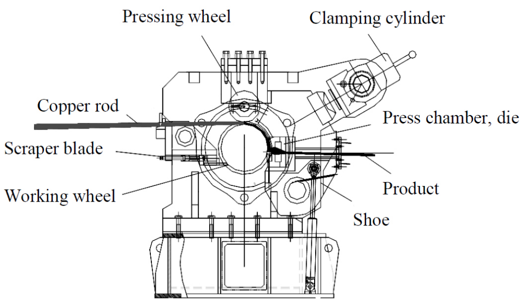


Fig. 1- Scheme of the Conform extrusion process [6].

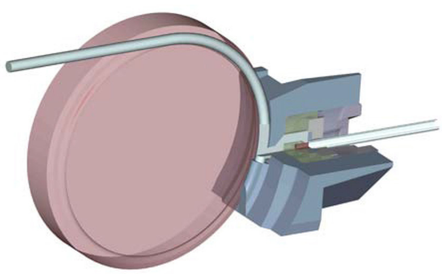

Fig. 2- Process of Conform 350i [7].

from both sides of the chamber, two rods of raw material are fed into the machine, which allows you to balance:

- direct coating-coating directly on the core of the material to be processed;

- direct application of the shell under high pressure-processing the core of the material under maximum displacement pressure to create a bundle of metals. In this case, before feeding the material to the Conklad machine, the core goes through a preheating stage (Fig. 3) [7];

Indirect application of the sheath or wrapping is used in cases where the core is extremely fragile or sensitive to high temperatures. In such cases, a larger winding is made, which is then applied directly to the core.

The Conklad process is used for manufacturing coated wires, pipes, and cables in a shell.

In the Conklad process, the bottom of the press chamber is heated by a disk, and the upper part is cooled by a pad that provides the closing force. Although the heating is from the side, the difference between the temperature in the upper and lower parts affects the metal being fed. When increasing the size of the shell, it is necessary to increase the difference between temperatures, and when working with materials with a diameter of approximately 50 mm, it is almost impossible to control the uniformity of the laye.

The patented SheathEx process (Fig. 4) is BWE's latest innovation [7].

Metal winding is used to protect cables from moisture without reducing their flexibility. Moisture penetration has a negative impact on the integrity of the insulation. Moisture combined with a high electrical load leads to the development of water tripping, which leads to premature cable failure.

The efficiency of using aluminum windings is confirmed economically, in addition, such products have better mechanical properties compared to products in lead winding. After forming, the aluminum coil can be compressed, as with the SheathEx process.

The SheathEx process, used for applying a seamless aluminum shell to medium-and large-sized power cables, is directly related to the recently introduced induction heating technology.

Processes such as ECAP-Conform allow you to get long semi-finished products (wire, wire rod, rods) with a UFG structure and have a high metal utilization rate. However, these methods have a drawback associated with multi-cycle processing and the fact that to obtain a high set of properties in metal materials, it is usually required to conduct 3-8 cycles of pressing a single workpiece. To solve this problem, the authors [8] a new SPD method–Multi-ECAP-Conform (Multi-ECAP-C) has been developed, which provides a high level of accumulated deformation in one processing cycle and intensive grinding of the original structure.

The process is implemented as follows (Fig. 5): the billet 1 is fed to the input of the working channel formed by a rectangular engraving of the rotating wheel 2 and a fixed clamp 3. By rotating the wheel 2 and the resulting active friction forces between the engraving of the wheel 2 and the workpiece 1, the pressing force is provided, leading to the promotion of the workpiece 1 through the working channel. The working channel in the output part has two step bends, which provides a sequential three-fold deformation by shifting the workpiece 1 under continuous processing conditions.

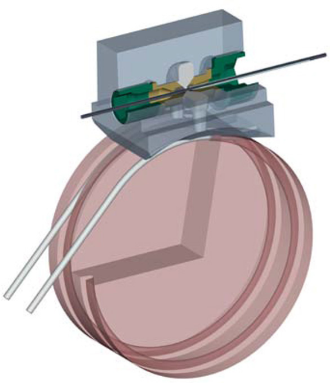

Fig. 3- Conklad process [7].

Fig. 4- SheathEx process [7].

One of the methods for obtaining long-length blanks is Linex, which is proposed by specialists of the company «Western Electric Co» (USA) [9-11]. Continuous pressing occurs due to active friction forces that occur between the flat surfaces of the chain links and the upper and lower planes of the workpiece having a rectangular cross section. The value of the pressing pressure depends on the difference between the friction forces on the oiled and non-oiled planes of the workpiece. This method is used for the production of aluminum tires and wire in the factories of the company «Venscuck» (USA). The maximum value of the extraction coefficient is an order of magnitude smaller than when implementing the method of Conform, which is the main drawback of this process. The scheme of this method is shown in fig. 6.

The Extrolling process was proposed in 1975 and patented by B. Avitzur in 1976 [12-13]. This method combines rolling and pressing in one deformation center. The main difference between this method and the Conform is more efficient filling of the gauge cavity with the metal of the workpiece and less power loss on the friction of the reactive action. The disadvantage of the process is a small single compression and a limited length of the resulting product. This method has not found industrial application, since it does not provide a steady flow of metal and create the necessary pressures for metal extrusion. The process diagram is shown in fig. 7 [14].

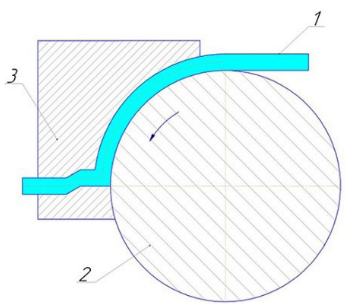


Fig. 5- Scheme of Multi-ECAP-C: 1 – billet; 2 – driving wheel; 3 – fixed clamp [8].

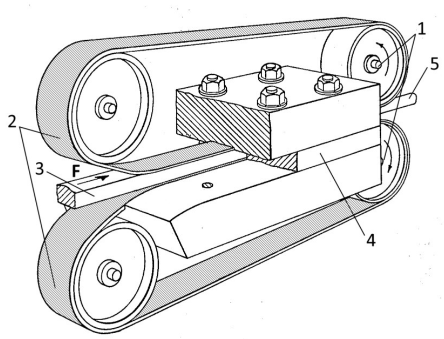


Fig. 6- Scheme of Linex continuous pressing process: 1 – rollers; 2 – links of endless chains; 3 – workpiece; 4 – matrix; 5 - finished product [11].

To carry out the process, the initial blank is continuously set in the gauge, compressed in it, which fully corresponds to the rolling stage and squeezed out into the calibration hole of the matrix installed at the exit of the gauge.

This method is implemented both in the cold state and at elevated temperatures and has less power loss on the friction of the reactive action, as well as more effective filling of the caliber cavity with the metal of the workpiece. The process in question combines the low friction losses and short processing time that are typical for rolling, and the high degrees of deformation that are possible during pressing. Disadvantages of rolling (small single compression) and pressing (limited length of the resulting product) with this implementation of the process can be eliminated. However, the method did not find proper application in industry, since the proposed technical solution (the use of an open gauge, the location of the matrix on the common vertical axis of the rolls, etc.) did not provide a stable flow of the process and create the necessary pressures for metal extrusion [15].

The Extrolling process has been modernized and developed as a combined rolling and pressing (CRP) method. The method is based on the deformation of a long blank of rectangular cross-section in a two-roll closed gauge, overlapped at the output by a matrix.

The essence of the proposed method of deformation is as follows. Pre-heated to the temperature of the beginning of deformation, the workpiece is fed to the rolling rolls, which, due to the forces of contact friction, capture it in the

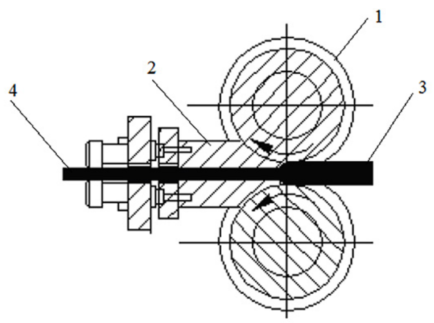


Fig. 7- Scheme of device for Extrolling process: 1 – work rolls; 2 – matrix; 3 – billet; 4 – product [13].

mouth of the rolls, and at the exit from it, push it through the channels of an equal-channel step matrix. After the blank is completely out of the mouth of the rolls, the next blank is fed to them, which, after passing through the rolls and getting into the matrix, pushes the previously formed blank out of the matrix. That is, in this case, the process of pressing blanks in an equal-channel step matrix is realized by using contact friction forces that occur on the surface of the metal contact with the rotating rolls [16].

In work [17] it is shown that a recrystallized dispersed structure is formed in aluminum semi-finished products after treatment with the CRP method. The disadvantage of this method is that when it is implemented, a high inhomogeneity of the deformed state is formed in the deformation center and, accordingly, the inhomogeneity of the properties of the final product. Stagnant zones are formed in the deformation center, which, as is known, leads to an increase in the pressing force and, consequently, an increase in energy consumption.

Fig. 8 shows the process of combined casting and rolling-pressing (CCRP) [18].

The main feature of this development is the use of a variant of the ECAP method in parallel channels, which leads to a significant change in the deformation scheme at the pressing stage compared to the known CCRP process. The molten metal 2 is poured into the furnace-mixer 1, and its crystallization begins on the surfaces of the rolls 3 and 4. Next, the crystallized metal is captured by rolls 3 and 4, rolled, decompressed and deformed in the channel of the matrix 5 in four consecutive continuous stages. At the first stage, direct compression is performed with a true degree of deformation ε ≥ 1.6. In the second and third stages, angular pressing is performed, which usually leads to an increase in the uniformity of the metal structure. And at the fourth stage, the calibration operation is performed by direct pressing through the circular calibration part of the matrix channel 5 [19].

The disadvantage of this device and method is that the contact surface of the matrix with the pressed material is made flat, which leads to increased pressing forces and the appearance of stagnant zones in the deformation center. In this regard, this method has limited functionality due to the fact that it does not provide a uniform deformed state and structure of products and, consequently, does not provide uniform mechanical properties. In order to eliminate the above shortcomings, a device for continuous casting, rolling and pressing of aluminum alloys using the SPD method had been developed. The device includes a furnace 1 with controller 2 flow of the melt in the caliber rolls, roll 3 with a brook and roll with a ledge 4 located on the frame 5 having cavities 6 for cooling and forming a closed caliber, closed at the output of the pre-chamber 7 cooling channels 8 and the die 9 with wedge-shaped cavities for cooling 10. For preloading the matrix and prechamber to the rolls, there is a hydraulic clamp 11, and for winding the finished press product into the bay - a winder 12 (Fig. 9) [20].

The created prerequisites made it possible to further develop the combined processes. For example, scientists in the United States of America [21] have proposed a new method for implementing

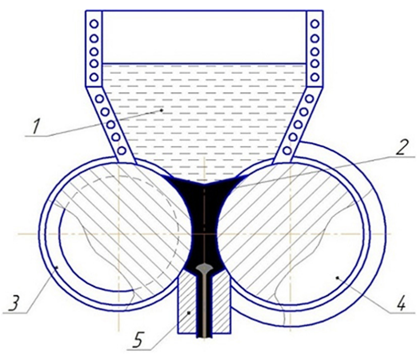

Fig. 8- CCRP process: 1 – furnace mixer; 2 – molten metal; 3, 4 – rolls; 5 – matrix [19].

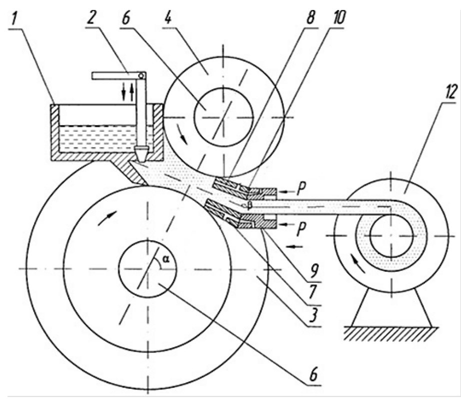

Fig. 9- The device for continuous casting, rolling and pressing: 1 – furnace mixer; 2 – regulator; 3 – a roll with a groove; 4 – a roll with a ledge; 5 – frame; 6 – cavities for cooling; 7 – prechamber; 8 – the cooling channels; 9 – matrix; 10 – wedge-shaped cavities for cooling; 11 – hydraulic clip; 12 – winder [20].

the shear mechanism of deformation of long workpieces through an equal-channel angular matrix. The schematic diagram of a continuous ECAP is shown in fig. 10.

The publication [68] touches upon an interesting topic of combining the process of continuous extrusion and longitudinal rolling (Fig. 11) for obtaining copper strips. The authors, using finite element modeling in the DEFORM-3D software package, determined the dependence of extruding and rolling speeds on the geometric dimensions of the strip and the degree of relative strain, from which several equations were derived.

A similar severe alternating deformation method is proposed to implement during rolling of thick slabs in the double SPD stand (Fig. 12) [23]. Rolling occurs without the billet widening due to the presence of non-driven edging rolls. The surface shape of rolls in the first stand made in the form of alternating annular blockers and collars with the same radius [24].

The conshearing process (Fig. 13) is a continuous version of the Equal Channel Angular Extrusion [25]. This process is not only productive but also applicable to coiled materials. Given that simple shear deformation is continuously imposed on coiled strips, the process can be used as a texture-control method. In previous papers, this process was successfully applied to an aluminum alloy 5 and an interstitial-free steel 5, and the formation of shear textures was reported. Meanwhile, ECAE was intensively studied as a severe plastic deformation for ultra-grain refinement. If continuous SPD of coiled materials is feasible, industrial applications of ultrafine-grained materials is much promoted. Although accumulative roll-bonding has been widely studied, research on continuous ECAE processes is rather limited.

As shown, the material is fed into the gap between a large central roller surrounded by satellite rollers by rotation of all rollers to generate enough extrusion force for deformation. Experiments on the conshearing processing of commercial purity aluminum samples demonstrated that optimum condition was obtained in the angle of 65° in ECAP zone. However, for successful operation a large number of rollers in required to deliver a large amount of extrusion force. This process was successfully implemented on an aluminium alloy and the formation of shear texture was reported making the process to use as a texturecontrolled method. This process is also applicable to coiled materials provided that some change in apparatus is made.

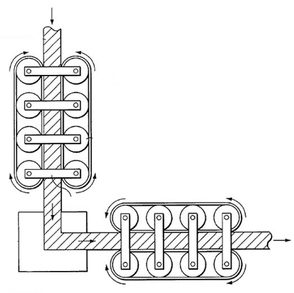

Fig. 10- Scheme of continuous ECAP [21].

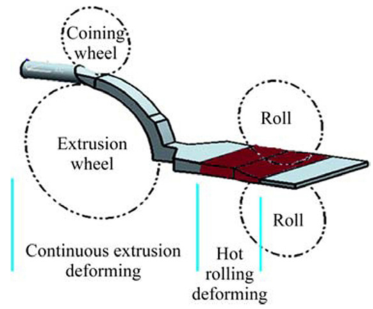


Fig. 11- a: Principle of continuous extrusion and rolling [22].

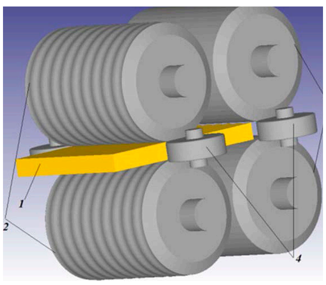

Fig. 12- The solid model of the double SPD stand: 1 – billet; driven horizontal rolls with section shaped 2 and smooth 3 barrels, 4 – non-driven edging rolls [24].

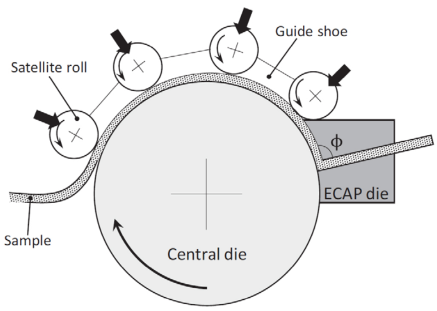


Fig. 13- Schematic illustration of the principle of the conshearing process [25].

Continuous Cyclic Bending (CCB), the scheme of which is shown in Fig. 14, was developed as a deformation method using specially designed rollers. This process provides bending deformation on strips/sheets. In this process, the outer layer experiences more deformation than the central part of the specimens, this leads to a certain difference in the accumulated strain energy between the central layers and the surface. Therefore, subsequent annealing after deformation in CCB gives the possibility to obtain a gradient microstructure with a fine-grained central layer and a coarse-grained surface layer. Although the process is continuous and simple, there are still a large number of drawbacks. Unfortunately, the small amount of deformation, the very small hydrostatic pressure, the almost complete absence of shear deformation, and the existence of tensile deformations at the surface make the process very useless [26].

Constrained groove rolling (CGR) as a continuous SPD method based on its discontinuous counterpart (constrained groove pressing) is developed as illustrated in Fig. 15 consists of two sets of grooved and flat rolls [27]. A sheet/strip/plate sample is corrugated and then flattened continuously between the rolls. At the corrugation stage, the workpiece is pressed between the asymmetrically grooved rolls in which the flat regions of the workpiece remain undeformed while the inclined regions are subjected to shear deformation. Then, at the flattening stage, the deformed regions experience reverse shear deformation while the undeformed regions remain still unchanged. Afterward, the workpiece is rotated by 180° and the undeformed regions are deformed by the rolls in which both stages are repeated to finish the first pass CGR. The CGR looks more practical since the material can be continuously deformed. However, free deformation and low hydrostatic pressure limit its industrial applications because of the less mechanical properties compared to most continuous SPD methods such as ECAP-conform [28].

Another way to intensify the shear deformation during rolling is longitudinal rolling with forced transverse displacement of the billet. To implement this method was developed a special two roll rolling mill, the distinctive feature of which is an individual drive of each work roll from the hydraulic servomotor. In this case, in addition to rotation, the bottom work roll also receives axial reciprocating motion from the hydraulic vibrator. To control the oil supply from the hydraulic power unit to the vibrator and servomotors, a computer is used, which synchronizes the rotation and axial oscillations of the rolls. The rotation of the rolls generates high compressive stresses in the material, and the forward motion of the bottom roll in the direction perpendicular to the rolling direction leads to shear deformations. As a consequence, during longitudinal rolling with transverse shear, intensive strip widening is observed. In this case, the main parameters affecting the process of structure formation are the degree of compression, the coefficient of friction between rolls and billet, the frequency and amplitude of oscillation of the bottom roll. In this case, the magnitude of compression per pass should be large enough to ensure that the friction forces arising during rolling provide not only the capture and supply of metal in the center of deformation, but also the shear of the material during axial displacement of the bottom roll.

The main disadvantage of the previous methods is the need to use specialized equipment and/or deforming tools for their implementation. Therefore, one of the most promising and highly effective methods of obtaining ultrafine grain structure is asymmetric rolling, which differs from the traditional one only in the fact that the billet is deformed between rolls of different diameters or rolls rotating at different speeds. To date, asymmetric rolling (between the rolls of unequal diameter) was used mainly in the manufacture of blooms, slabs,

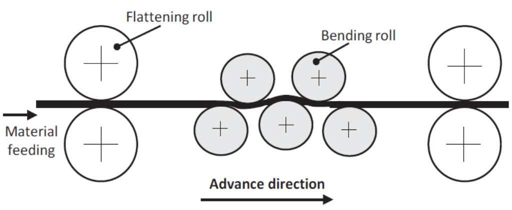


Fig. 14- Roll driven CCB machine [26].

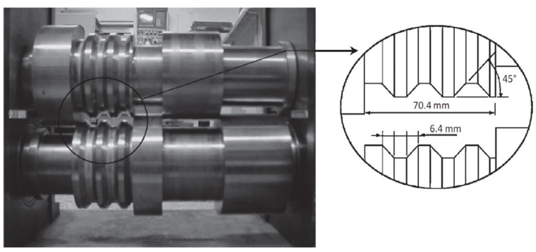


Fig. 15- Photograph showing the CGR apparatus [27].

billets and large shapes for strip bending upwards by the difference in circumferential speeds to prevent strips coming out of the rolls on the rolls, as well as when rolling in section mills for bending strip on the bottom guides to ensure its straight output from the sire. Due to differences in the speed of rotation of rolls or their diameters - on the contact surfaces of the metal with the rolls deformation resistance of the upper and lower layer of the strip is different, which affects the length of the arc of metal contact with the roll, the distribution of contact stresses and the average value of contact pressure. In other words, asymmetric rolling forms an asymmetric center of plastic deformation, which leads to large shear deformations, and as already mentioned - this is a necessary condition for SPD and obtaining ultrafine grain structure. Therefore, at present, studies of asymmetric rolling of sheets and strips are actively carried out.

## 3. Analysis of ways of continuous wire nanostructuring

Despite the disadvantages, traditional drawing remains beyond competition and is the only mass method of wire production. Continuous improvement of drawing by applying new drawing lubricants and designs of drawing tools, effectiveness of wire and fiber cooling has not resulted in a clear qualitative breakthrough. The solution of the problem consists not only in improving the method of drawing, but also in creating new technological processes of wire production on the basis of the traditional process, considering these processes as the next evolutionary stage in the development of drawing.

It is necessary to note that drawing through monolithic drawings is a conservative process as there is practically no possibility of active control of the stress-strain condition in the deformation zone during processing which considerably defines the quality of the finished products and process efficiency. Development of improved drawing processes, allowing by changing the technological factors of the process to control the plasticity and deformability of the metal is an urgent task.

Wire from various metals and alloys occupies a significant place in the overall structure of metal production. However, the existing production facilities are not able to meet the possible growth of domestic demand for wire. Therefore, the development of our own capacities, the use of the latest processing technologies, and the development of new methods for processing metals by pressure are the main directions of development of the wire industry.

Traditional deformation technologies, such as drawing and cold rolling, are accompanied by grinding of the structure. However, the substructure has a cellular character with grains elongated in the direction of drawing or rolling, and also contains a high proportion of small-angle boundaries.

Paying more attention to the drawing process as one of the basic continuous methods of wire drawing, it can be argued that at the moment there is a complication of the classical method of drawing by combining with other effects on the metal or expanding the range of technological modes of drawing [29,30].

A different-named scheme of the stress state of the metal in the deformation zone during drawing, characterized by one tensile and two compressive main stresses, creates conditions under which the plasticity of the stretched metal is significantly lower compared to almost all pressure processing processes, except for stretching. This fact determines the relatively low unit strains in the transition. The odds of drawing at drawing rarely exceed a value of 1.5. To restore plasticity, it is necessary to use more frequent intermediate heat treatments than in other metal forming processes.

Based on the combination, a method was developed for producing ultra-fine-grained semi-finished products by drawing with alternating bending with torsion [31]. The schematic diagram of the continuous method is shown in fig. 16.

In accordance with the presented scheme, a steel wire with an initial diameter of $d_0$ is loaded into the first fixed conical drag along its course and then sent to a system of rollers that provides alternating bending of the wire. Then it, having a diameter $d_1 < d_0$ after the first wire, enters the second fixed conical wire of smaller diameter located coaxially with the first, after which the wire has a diameter $d_2$, followed by fixing its front end in the winding device. After that, the process of sequential

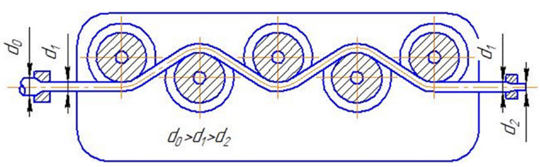


Fig. 16- Scheme of wire production by drawing treatment with alternating bending with torsion [31].

combined deformation of the metal by drawing is carried out due to the pulling force created by the rotation of the winding device [31].

To implement the continuous method, a device was developed for the production of wire with an ultra-fine-grained structure, for which a patent for utility model [32] was obtained. The principle of operation of the device is explained in fig. 17.

This device comprises a coaxially installed in the direction of drawing input drawing die 1, located in the fiber holder 2, rigidly fixed on one side of the stationary frame 3, a drive mechanism 4 for torsion and alternating deformation of the workpiece 5 and an output drawing die 6, installed in the fiber holder 7, located on the other side of the frame 3. The drive mechanism 4 is installed with the ability to move it along the longitudinal axis and then fix it firmly in the specified position. This technique allows you to adjust the degree of torsion deformation within optimal limits, improving the mechanical properties [32].

For the experiment, a device was selected in [33] to implement a continuous method of deformation nanostructuring of wire by bending and torsion. The essence of the method consists in imposing of tensile and compression deformation on a continuously moving wire while it passes through serially set fibres with a simultaneous application of bending and torsion deformation in a four-roller unit which has an individual drive, thus allowing a wide range of changing the degree of torsion deformation.

In this case, due to large shear deformations occurring in the processed wire under combined deformation influence, a UFG structure is formed with an appropriate level of physical and mechanical properties in the wire of a wide size and grade assortment. The advantage of this method is the possibility of its use in industrial wire production technologies, since the speed of such processing is compatible with the speeds of coarse and medium drawing. Besides, use of the tool of hardware production does not require significant re-equipment of existing drawing mills. The main technological parameters of the process, affecting the formation of UFG structure and mechanical properties of the wire are the compression in the drawing and the number of twisting turns. The influence of various technological factors of the developed combined processing on the formation of UFG structure of medium-carbon wire of various diameters is well enough studied [34]. It was shown that the combination of different types of plastic deformation allows to obtain a different combination of strength and ductility on the wire of the same steel grade and diameter. This is a distinctive feature of combined deformation by drawing with bending and torsion.

Many of these methods are based on bending, such as multiple angular accumulative drawing (AAD), described in [35] (Fig. 18). In contrast to ECA-broaching, the AAD method is characterized by a complex mode of changing the type of deformation – diameter compression, stretching and torsion, which affects the change in the microstructure of the final product, which, with appropriate control, leads to improved properties, which is especially important for alloys that are not characterized by a complex composition.

In the ECA-broaching and AAD method, the strains of stretching, compression, bending, and torsion are carried out in more than one deformation center. Thus, compression deformation occurs in the drag, stretching and torsion in the gap between the lugs. However, in the production of long products, it is impractical to use methods based on bending because of the imperfection of the tooling and the complexity of embedding it in existing equipment.

There is a known process of rolling with the imposition of longitudinal shear deformation

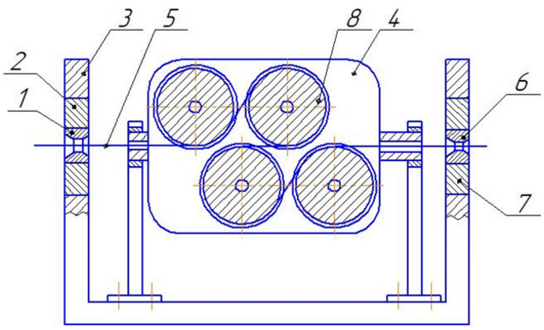


Fig. 17- Device for implementing a continuous method for obtaining UFG wire: 1 – drawing die; 2,7 - fiber holder; 3 – frame; 4 – drive mechanism; 5 – workpiece; 6 – drawing die; 8 – roll [32].

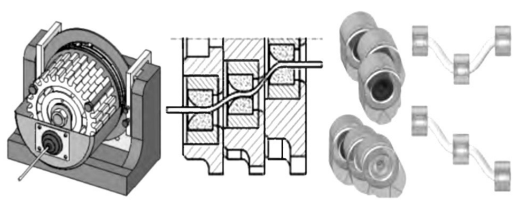

Fig. 18-Repeated angular accumulative drawing (Accumulative Angular Drawing process - AAD) [35].

(called the "rolling-drawing (RD)" method). In comparison with the conventional rolling method, significantly lower rolling forces are applied at the RD and greater compression is achieved [36].

The essence of the process is the deformation of the strip between the rolls rotating at different speeds ($v_{b1}$-the circumferential speed of the driving roll, $v_{b2}$-the circumferential speed of the driven roll), and the ratio of the roll speeds is equal to the drawing (Fig. 19).

Tension is applied to the ends of the strip to create rest on the arcs of the coverage of friction. The velocity of the rear end of the strip is automatically maintained equal to the peripheral speed of the driven roll and the speed of the front end equal to the circumferential speed of the leading roller. In this process, the ratio of the rotation speeds of the rolls is proportional to the exhaust. The draw is variable and difficult to hold, especially when drawing [37].

The authors [38] developed a method of rolling-drawing through an equal-channel angular matrix

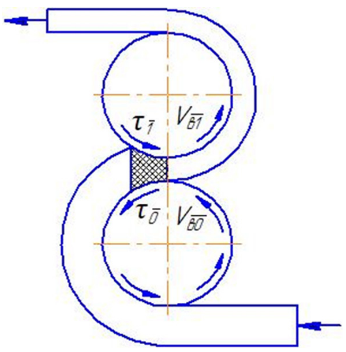

Fig. 19- The scheme of the rolling process with the imposition of longitudinal shear deformation (rolling-drawing) [36].

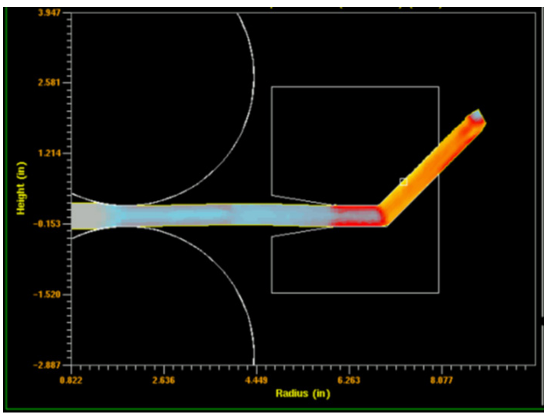


Fig. 20- Rolling-drawing in an equal-channel angular matrix: a – mathematical model of process; b – experimental installation [38].

with intersection angles of 1350 and 1200 (Fig. 20), the material is an aluminum alloy AA6061, with a width and height equal to 12.5 mm and a length of 1.5 meters. At the same time, the degree of accumulated deformation at an angle of 1350 per pass was ≈ 0.5. Eight passes were completed successfully. Deformation with an angle of 120° was also performed. According to the authors ' recommendations, the compression in the rolls for the first pass should be 2%, for the second and third 1% [39-43].

The authors [44] proposed a method for continuous deformation of metal products of different cross-sections. The process involves implementing a continuous deformation cycle through an equidistant multi-angle matrix. As in the proposed method, the problem with the implementation of feeding the workpiece to the tool is solved by using a set of notched rollers (Fig. 21).

In one of the applications of this method, it is proposed to use a pair of similar rollers in order to pull the workpiece out of the matrix, then the workpiece is wound on the drum to ensure continuity.

At the same time, one of the important conditions of the process is to maintain equality of speeds at the input and output of the tool of the traction and pushing tool. It is also proposed to use smaller diameter rollers as a calibration pass, and the corresponding adjustment of the roller rotation speeds is necessary. In this method, in order to reduce drag from the vertical channel, it is proposed to make significant rounding of the joints, which directly reduces the index of shear deformation.

The idea proposed by Suriadi et al. [45] to push the workpiece through intersecting channels in order to eliminate the problem associated with the compression load at the ECAP gave rise to a new concept in the SPD, known as equal-channel angular drawing (ECAD). ECAD has significant

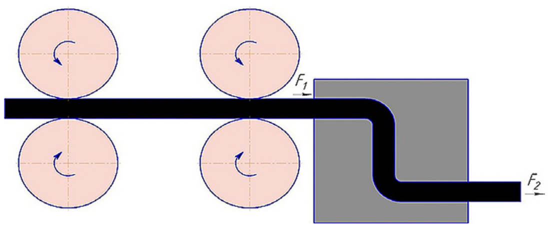


Fig. 21- Schematic representation of the workpiece in a continuous process with a multi-angular equally channel pressing [39].

advantages over ECAP. Firstly, the length of the workpiece is not limited by the technological parameters of the process, namely the instability of the pressure punch, and, secondly, ECAD can be used as an intermediate operation in other related industries. The peculiarity is that the flow pattern of the material is more similar to the bending during tension. In this method, the blank is first bent to fill the channels of the matrix, and then stretched.

However, this process is not without drawbacks. Thus, when the workpiece passes the shear plane, the introduced shear deformation also leads to a certain change in the cross section, namely, to the thinning of the workpiece [45].

The authors of works [46-50] proposed the ECAP-drawing method. This method of deformation, shown in fig. 22, due to the combination of two methods: intensive plastic deformation in an equal-channel step matrix and the drawing process, allows you to obtain a wire of the required size and shape of the cross section, which has an ultra-fine-grained structure. At the same time, restrictions on the length of the initial blank are removed, and the length of the finished products can reach several tens of meters.

The essence of the proposed method of deformation is as follows. The pre-pointed end of the wire is set in an equal-channel step matrix, and then sequentially in the calibration drag (in essence, the process of the metal task does not differ from the task of the wire in the drag in the standard drawing process). After the end of the workpiece comes out of the portage, it is fixed with gripping tongs and wound on the drum of the drawing mill. In this case, the process of pulling the workpiece through an equal-channel step matrix and a calibration drag is realized by applying a pulling force to the end of the workpiece. An external load is applied to the metal being stretched, and contact stresses occur on the metal-tool contact surface. In contrast to other methods of processing materials by pressure, the implementation of which cannot be carried out without the presence of contact friction forces, when drawing on the metal-tool section, directed against the movement of the metal, are negative phenomena of the process, which undoubtedly implies the use of technological lubricants that reduce friction [50].

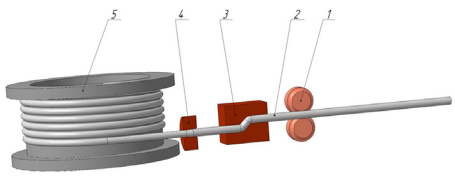


Fig. 22- The scheme of the combined process "ECAP-drawing": 1-setting device; 2 – wire; 3 – equal-channel step matrix; 4 – a drawing die in the die-head block; 5 – drum [47].

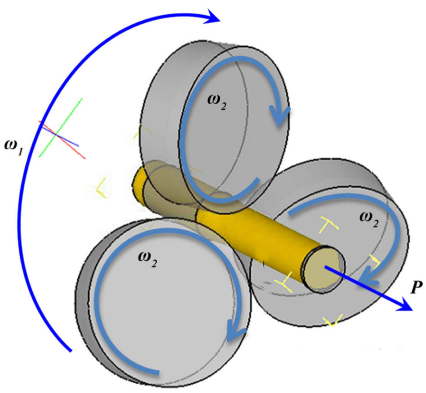


Fig. 23- Principle diagram of the RSPr. $\omega_1$ - rotation speed of the cassette; $\omega_2$ - rotation speed of the rollers; P - pulling force [56].

This method of deformation also makes it possible to process various bimetallic wires [51-55].

There is a method of radial-slide broaching (RSBP), which is based on the principles of radial-slide rolling. RSPR is carried out by applying a forward pulling force to the wire (rod) without twisting it (Fig. 23). Installation of radial-sliding broaching is a cassette with 3 non-driven rollers, located at an angle of 120° to each other, with feed angles β>16°. Each roller has a working cone and a calibrating belt. The distinctive feature of the RSBP process is that it can be carried out on operating drawing machines, installing a cassette of radial-sliding broaching instead of a fiber holder [56].

This device comprises a coaxially installed in the direction of drawing input drawing die 1, located in the fiber holder 2, rigidly fixed on one side of the stationary frame 3, a drive mechanism 4 for torsion and alternating deformation of the workpiece 5 and an output drawing die 6, installed in the fiber holder 7, located on the other side of the frame 3. The drive mechanism 4 is installed with the ability to move it along the longitudinal axis and then fix it firmly in the specified position. This technique allows you to adjust the degree of torsion deformation within optimal limits, improving the mechanical properties [56].

It is also worth noting the method of equal-channel angular free broaching (ECA-broaching), which leads to the formation of a UFG structure in long blanks of a round cross-section (Fig. 24) [57].

This process consists in repeatedly pulling the wire through special matrices, in the design of which two channels intersecting at an angle are provided. In [58], the influence of heat treatment and matrix design on the mechanical properties of the resulting samples is studied. It is also shown that to obtain a UFG structure, it is necessary to conduct from 4 to 10 processing cycles, which is the main drawback of this process. It is worth noting that when ECA-broaching in the processed workpieces, a non-uniform UFG structure is observed even after 8 passes.

**4. Prospects for the development of SPD methods**

The development of technologies related to the research, creation and use of nanomaterials in the coming years will lead to dramatic changes in many areas of human activity - electronics, computer science, materials science, energy, engineering, biology, medicine, agriculture, ecology.

Nanotechnology is considered by the leading countries as a lever for gaining world economic, financial, political and military domination. The object of research in these countries is a wide range of nanomaterials of the structural and functional classes, nanomaterials for electronic engineering, biotechnology and medicine, etc.

Material science of structural nanomaterials is a complex of scientific and technological problems, the solution of which should be aimed not only at studying the scale factor (reduction of the size of particles, elements or structures), but also at investigating fundamentally new phenomena inherent in the nanoscale.

The creation of structural nanomaterials is at the initial stage of development of useful for practice directions of research and development and requires the use of a wide range of new nanotechnologies.

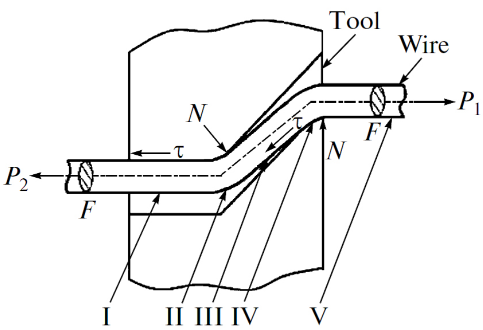


Fig. 24- System for free extension of wire in bent uniform channels: $P_1$, extension force; $P_2$ counterforce; N, normal pressure; τ, frictional force [57].

Creation of structural nanomaterials through structure fragmentation by severe plastic deformation methods has become one of the most researched areas in recent years. The solution of such complex problems of modern materials science requires a large cycle of fundamental and applied research both in the development of the most important science-intensive nanotechnologies and in the creation of a diagnostic base.

To date, an experimental sample of protective vest has been created and tested under real working conditions on a welding machine of medium power at an arc current of 110-120 A° [59]. The tests showed that inside the vest the levels of magnetic field induction decrease by 10-15 times and are 70-100 μT. Thus, in the area of human body when using protective clothing based on amorphous alloys with nanocrystalline structure it is possible to significantly reduce the field more than 10 times and optimize working conditions of personnel.

At present works on essential extension of fields of practical application of the developed screens are being carried out, in particular for creation of magnetic screens, providing effective protection against direct and alternating magnetic fields in the form of roll materials of MAR-1K and MAR-1F types, cables of AVVG type, and also screened cells and rooms for protection both of biological objects and high-precision devices against influence of external magnetic fields [60].

Several thermochemical reactor designs have been developed based on the above nanodevices. The most promising is their use in power units of transport systems and hypersonic aircraft operating on hydrogen fuel.

Another promising application of nanocomposites is the creation of hydrogen storage structures (getters).

One of the effective materials-getters are intermetallides of the “titanium-aluminum” system. Additional introduction of niobium in the Ti-Al system leads to improved properties of adsorption-desorption of hydrogen due to the formation of nanoscale phases with less dense packing compared to the GPU-lattice $Ti_3Al$. The most promising for hydrogen absorption is the O-phase based on the orthorhombic lattice $Ti_2AlNb$. Also researches on hydrogen absorption by alloys of “titanium-aluminum-niobium” system at temperature 450-480°C and excessive hydrogen pressure 4 atm were carried out. The alloys of three compositions were tested: Ti-30Al-16Nb-1Zr-1Mo, Ti-13Al-37Nb, Ti-

11Al-40Nb. It was found that with an increase in the niobium content from 16 to 40% wt. there is an increase in hydrogen absorption from 0.47 to 2.5% wt. of hydrogen [61].

The results obtained allow us to speak about the promising use of severe plastic deformation in various fields [62-64].

## 5. Summary

In recent years, new ways to improve the properties of structural materials through the purposeful formation of ultrafine grained structure of metals and alloys during various types of deformation action have emerged. Changing the grain size through deformation can significantly improve the mechanical and physical characteristics of metals and alloys. Existing methods of severe plastic deformation for shaping the UFG structure of metals, such as equal-channel angular pressing, high-pressure torsion, multi-axis deformation, helical extrusion, etc., have significant limitations on the industrial implementation, due to the limited size of the processed workpieces, the discrete processes, the complexity of the equipment and tooling used, incompatibility with the speed and strain modes of technological processes of metallurgical and metalware production. From this point of view, one of the pressing problems currently being addressed by researchers is the creation of methods of deformation nanostructuring of metals and alloys, which by their technological parameters and productivity could be adapted to the current industrial production. Recently, one of the promising trends in the development of technological processes for the production of metal products is the combination of various processing methods (rolling, drawing, extrusion, pressing, etc.). In our review it is shown that the use of combined action in the production of long billets provides the formation of UFG structure with the corresponding to this structural state level of mechanical properties.

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