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Analysis of modern technologies for the implementation of severe plastic deformation to obtain an ultrafine-grained structure

Abstract: The paper presents an overview of the latest achievements in the development of severe plastic deformation (SPD) processes to obtain an ultrafine-grained structure. The action mechanism of shear and alternating deformations, which are the basis of these processes, is described. It is shown that the most well-known SPD processes -high-pressure torsion (HPT) and equal-channel angular pressing (ECAP) - are unsuitable for economically justified wide industrial applications due to a number of technological disadvantages. This problem can be solved by ensuring the continuity of the deformation process and the possibility of long blanks deformation. As a result, in recent years, a number of combined metal forming processes, which are a combination of two or more conventional deformation processes. This concept is the most promising direction for the development and improvement of metal forming methods. The proposed new concepts of combined processes of severe plastic deformation are aimed at further improving the deformation performance, since the presence of the ECAP scheme in all three proposed variants will allow deforming without significantly changing the initial dimensions of the workpiece.

*Keywords:* severe plastic deformation, ultrafine-grained structure, high pressure torsion, equal-channel angular pressing, combined processes.

Introduction: Effect of Shear and Alternating Deformation on the Ultrafine-Grained Structure Production

Improving the quality of metal processed by various deformation methods is a priority task when developing a fundamentally new or upgrading a well-known metal forming process. The required properties of deformable materials can be provided by creating conditions for the formation of an ultrafine-grained structure [1]. Ultrafine-grained (UFG) materials have a grain size of less than one micron and are divided into nanocrystalline (d <100 nm) and sub-microcrystalline (0.1<d<1 µm). Severe plastic deformation is one of the most effective ways to form an ultrafine-grained structure in metals, since various deformation processes are used not only to give the processed metal the specified geometric dimensions, but also to obtain the required properties.

It is extremely difficult to obtain an ultrafine-grained structure using traditional metal forming methods. It was noted in [2] that when choosing a deformation scheme, preference should be given to schemes where a pure shear is realized, since in this case a minimum amount of energy for deformation is spent, maximum and uniform cross-sectional processing is achieved, a structure with specified physical and mechanical properties is obtained, internal defects of the cast structure are closed.

According to work [3], eleven types of plastic deformation mechanisms are possible, which are divided into three main groups: shear, diffusion and boundary. The group of shear processes includes normal shear, twinning, as well as bending and laminating. Usually, any deformation process is carried out with the simultaneous flow of several mechanisms. However, depending on the deformation conditions, one or another mechanism always prevails. The main mechanism of deformation is the normal shear, which allows to achieve the highest speeds and values of deformation.

It is known that the shear movements of some parts of the crystal relative to others are carried out with the help of numerous types of dislocation movements. Dislocations lead to an increase in potential energy and create stress fields in the crystal. Dislocation creeping, associated with changes in interatomic distances, causes deformation of crystals, and intense dislocation creeping and directed (due to the influence of external forces) diffusion of atoms leads to plastic deformations [4]. The movement of dislocations is carried out due to the action of shear stresses. The presence of dislocations contributes to the shear process, which can occur when relatively lower stresses are applied.

Macro-shears play an effective role in the deformation processing of the metal structure. This is explained by the fact that macro-shears initiate the mass development of unidirectional micro-shears in grains with different crystallographic orientation, while grain boundaries are not an insurmountable obstacle to their propagation. Due to the fact that the deformation effect of the cast metal processing is determined by shear phenomena, when determining the causes of the dependence of mechanical properties on the degree and scheme of deformation, shear deformations are taken into account. The aggregate structure of the metal consists of crystals oriented in different directions by crystallographic sliding planes, therefore, it can be considered as a quasi-isotropic material. Studies of the influence of plastic deformation mechanisms on changes in the metal structure have revealed that the development of shear deformations along the cross-section of the deformable sample leads to significant grain grinding [5-6]. Thus, severe shear deformations can be found practical application in various cases of plastic processing of metals and alloys in order to significantly improve their physical and mechanical properties.

In addition to shear deformation, an effective way to obtain UFG materials is the implementation of alternating deformation [7-8]. Its conditional scheme is shown in Fig. 1. At the first stage, the square element under the action of shear deformation changes its shape to a parallelogram. At the second stage, when the direction of the shear deformation changes, the element restores its original shape. It is established that with alternating deformation, the magnitude of the damage crterium is significantly less than with monotonic deformation. Thus, the implementation of shear and alternating deformations can provide a qualitative processing of the metal structure.



Figure 1 - Scheme of alternating deformation.

Use of SPD Methods in the Formation of an Ultrafine-Grained Structure

Over the past three decades, a large number of metal forming methods have been developed and researched to produce workpieces with an ultrafine-grained structure. These methods are based on various schemes of shear or alternating deformations. All these processes make it possible to implement a special type of metal forming, which "severe plastic deformation" is called.

Obtaining an ultrafine-grained structure by severe plastic deformation is possible under the following conditions [9-12]:

1) implementation of high degrees of strain for grain grinding (e > 6);

2) providing high hydrostatic pressure that prevents the sample destruction (1 GPa and above);

3) deformation at temperatures of about 0.4 of the melting point and below to prevent recrystallization;

4) ensuring the deformation non-monotonicity, which contributes to the formation of high-angle intergrain boundaries.

It is possible to obtain these conditions when processing metal by such methods as high-pressure torsion, equal-channel angular pressing, screw extrusion, comprehensive forging, and others.

High-pressure torsion is one of the oldest methods for obtaining bulk ultrafine-grained and nanostructured samples [13-15]. The samples obtained by this method have the disk shape. Using this method in various materials it was possible to obtain a structure with a grain size of up to 20 nm. However, HPT method has such significant disadvantages as the small size of the workpieces being processed and low tool life. Because of this, this method is still used only in laboratory conditions.

The equal-channel angular pressing (ECAP) is devoid of many listed disadvantages and allows to obtain samples of square or rectangular cross-section with a homogeneous ultrafine-grained structure with a grain size of 100-200 nm. This method was invented more than 40 years ago [16] for grinding the cast structure of ingots. The ECAP technology and its various variations is most fully described in [17], as well as in [18-21].

In the ECAP process various sliding systems can be involved in the processed materials due to the rotation of the workpiece around its longitudinal axis between each pass. In practice, four main pressing routes are carried out: route A — without rotation of the workpiece, routes BA and BC, involving rotation by 90° in different directions or one direction, respectively, and route C, involving rotation by 180°. In [22-24], it was experimentally shown that when using equipment with a channel intersection angle of 90°, the implementation of the BC route is the most effective for the formation of an ultrafine-grained structure consisting of homogeneous and equiaxed grains having boundaries with high misorientation angles. According to many studies, in order to obtain a uniform ultrafine-grained structure over the entire volume of the workpiece, four to eight passes with intermediate edging of the sample are required.

Among the new directions in ECAP is the hard-to-form materials processing. Experimental and theoretical modeling of the ECAP mechanics, associated with studies of the stress-strain state, contact stresses and friction conditions, made it possible to design tooling for obtaining large-sized blanks from various metals, such as copper, titanium, tungsten, aluminum, as well as in various alloys based on them [25-31]. This method is one of the most frequently mentioned in scientific articles devoted to the study of various ultrafine-grained materials. Also, this method has many variations of technical and technological execution [32-36], which are based on the principle of the shear deformations implementation.



Figure 2 - ECAP in a matrix with parallel channels.

Special attention should be paid to the stepped ECA matrix or ECA matrix with parallel channels [37-38], as can be seen in Fig. 2, which allows not only shear deformation to be realized when the workpiece passes through its channels, but also at the same time two alternating deformation zones, provided that the input and output channels are co-directional. This scheme is also energy-saving, since it allows to realize a large deformation degree in one pass. Due to the co-directionality of the input and output channels and a relatively small pressing force, matrices of this type are most convenient for creating combined processes.

A common disadvantage of the ECAP process is the need for a large deformation force when processing massive workpieces and low tool life. The described methods and devices are the most effective and popular for obtaining an ultrafine-grained structure, however, there are other methods that also allow obtaining such grain size by severe plastic deformation.

One of such deformation methods is the "hourglass", which consists in the implementation of uniaxial multi-cycle alternating deformation [39-40]. With this metal forming method, a cylindrical blank is pressed out by direct extrusion through a point of a movable matrix and at the output, due to an organized backup, it settles in a closed cylindrical cavity to the diameter of the initial blank preceding extrusion. If you apply an extrusion force to the deposited part of the workpiece from the other side, the process will repeat. Such a multi-cycle deformation scheme makes it possible to obtain an ultrafine-grained structure in workpieces with a diameter of 15 mm and a length of up to 100 mm.

Another way to obtain ultrafine-grained materials is screw extrusion [41-44]. The essence of this method lies in the fact that the prismatic workpiece is pressed through a screw matrix, the channel of which consists of three zones: entrance, screw, calibration. The geometric parameters of the cross sections of all zones are the same. Due to the specified features of the channel geometry, when the workpiece is pushed through it, its shape does not change, which allows for multiple extrusion of the workpiece in order to accumulate severe deformations. At the same time, its structure and properties change while maintaining the identity of the initial and final forms. The fiber located along the axis of the sample is subjected to minimal deformation, the fibers furthest from the axis are subjected to maximum deformation.

Having analyzed the listed methods for obtaining ultrafine-grained materials, it can be concluded that none of these methods, due to high energy consumption, is ready for economically justified wide industrial use. This problem can be solved by ensuring the process continuity and the possibility of long blank deformation.

Continuous Methods of Severe Plastic Deformation as a Solution to the Problem of Long Blanks Deformation

The metal forming methods discussed above relate to discrete and semi-continuous pressing methods [45-46]. These technologies have a number of disadvantages, the main of which are related to the discreteness (discontinuity) of the process and the implementation of the pressing scheme with the presence of reactive friction forces on the metal contact with the container. This leads to a limitation of the length of the pressed products, a decrease in their quality due to uneven deformation and high energy intensity of the pressing process. These disadvantages can be eliminated by applying continuous pressing schemes. This method is fundamentally different from the previous ones in that active friction forces are used to carry out deformation and extrusion of the workpiece through the hole of the matrix. A workpiece of unlimited length can be used in these methods. The main continuous pressing methods are Conform, Linex and Extrolling. Continuous pressing technologies and equipment allow solving the above-mentioned problems of discrete and semi-continuous pressing methods by concentrating the necessary deformation degree in the node of continuous deformation.

Among the listed methods, the Conform has a special place. It has a number of technical and economic advantages and a wide application scope. The works [47-50] provide an analysis of the technology and equipment of continuous pressing, as well as the results of research in this area. The Conform method is based on the use of a stationary tool called a shoe, a movable rotating wheel-type tool with a groove along the periphery, and a matrix is installed at the end of the shoe that overlaps the groove of the wheel. In the zone immediately in front of the die, the workpiece undergoes severe plastic deformation and fills the entire section of the groove (the capture zone during extrusion); this contributes to an increase in the friction forces between the surface of the groove and the workpiece. As the wheel turns, the compressive force applied to the workpiece increases and the force required to extrude the workpiece material through the hole in the die is achieved, i.e. the pressing process begins.

However, this method has a number of disadvantages that significantly limit its possibilities. To deform even soft aluminum alloys, large energy consumption is required, since the friction along the tool assembly is quite large. In addition, this also leads to a strong heating of the deforming tool and, as a result, to a decrease in its durability. The properties of press products are characterized by heterogeneity due to uneven deformation due to the creation of reactive friction forces at the metal - press assembly contact, which is not quite acceptable, for example, for electrical products.

A feature of the Linex method is that the pressure required for the implementation of the process is created through the use of active friction forces that arise between the flat surfaces of the links of infinite chains and the upper and lower planes of the workpiece having a rectangular cross section [51]. At the same time, the value of the pressing pressure turns out to depend on the difference in friction forces on the non-lubricated and lubricated planes of the workpiece.

The Extroling process [52] is a particular method of the Linex process. It is characterized by the fact that due to the active forces of contact friction between the rolls and the workpiece, extrusion is carried out through a pressing matrix. To carry out the process, the initial blank is continuously set into the gauge, crimped in it, which fully corresponds to the rolling stage and squeezed into the calibration hole of the matrix installed at the outlet of the gauge. This method is implemented both in a cold state and at elevated temperatures and has lower power losses due to reactive friction, as well as more efficient filling of the caliber cavity with the metal of the workpiece. The process in question combines the low friction losses and short processing time characteristic of rolling with the high single compression possible during pressing. The 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 ensure a steady flow of the process and the creation of the necessary pressures for metal extrusion.

Combined Methods of Severe Plastic Deformation

In recent years, there has been a tendency to develop combined metal forming processes, which are a combination of two or more conventional deformation processes. The main feature of combined processes is that often, when they are implemented, the disadvantages of conventional deformation processes that are included in the combined process are reduced or completely eliminated.

From this point of view, the rolling-pressing method based on the Extralling method is promising, where the extrusion is carried out due to the power of the active friction forces supplied by the rolls. Research in this area is devoted to works [53-56], aimed primarily at studying the distribution scheme of stresses and forces acting in the deformation zone. A comprehensive study of the reserve friction forces in the deformation zone during rolling, as well as factors affecting their magnitude [57-59], allowed to conclude that the sliding and sticking zones on the contact surface arise under the action of these forces. These forces can be balanced either due to tangential friction forces acting in the advance zone, or due to external influence in the form of a front support. In the case when the magnitude of the back-up force balances the reserve friction forces, the process proceeds with one lag zone on the contact surface.

The method proposed in [60], the "rolling through the matrix" was called. Its main difference is that a solid matrix is used, and the product is formed in two "transitions" of the mill due to the contact between the outer surfaces of the matrix and the surfaces of the rolls. At the same time, the metal flows around the matrix, dividing into two or more streams, which subsequently connect to form the shape of the finished product at the output of the two specified transitions. Studies of the "rolling through the matrix" process for the first time for continuous pressing methods were carried out on steel samples, which confirms the versatility and possibility of using these processes for most materials.

In works [61-64], studies of the shape change and energy-power parameters of the rolling-pressing process are presented. At the same time, the deformation conditions of lead and aluminum blanks were studied, the problem of estimating energy-power parameters by the power balance method was mathematically solved, and graphs to determine the possible degrees of deformation depending on various process factors were constructed. For the first time, experimental data and results of theoretical studies on energy-power parameters and conditions of the principal feasibility and stability of the rolling-pressing process were obtained, a process model was developed that allows calculating the design parameters and the created pressing pressures depending on the diameters of the rolls and their ratio, the size of the caliber, the distance of the matrix from the plane passing through the axes of the rolls, the size of the workpiece and the conditions friction.

In addition to combined rolling-pressing, other combinations of metal forming processes have also been developed. In work [65], the combined process of rolling and drawing is investigated due to the implementation of the angular pressing scheme. This method makes it possible to develop a deformation in the deformable metal sufficient to obtain an ultrafine-grained structure. However, in the course of analytical and experimental studies, it was revealed that due to the very strict boundary conditions in the drawing tool, it is possible to deform either a wire with a diameter of up to 6 mm, or strips with a thickness of up to 4 mm and a width of up to 120 mm in this way.

In works [66-67], the results of studies of the ECA – broaching process are presented. In accordance with the proposed method, the steel-copper wire is repeatedly stretched through a prefabricated tool of a special profile. The continuity of the deformation processing process is achieved by combining ECA - broaching with the traditional method of wire drawing. In order to ensure the efficiency and technological stability of the ECA - broaching is implemented when the tool is not fully filled with wire, which during processing keeps the cross-sectional area unchanged. The authors of this method of deformation carried out a study of the effect of multiple (up to 10 cycles) ECA - broaching on the microstructure evolution. It is shown that ECA - broaching is accompanied by significant fragmentation of the structural components of the surface and the central region of the samples. Already after two and up to 10 processing cycles, intensive grinding of the wire structure is observed.

The team of authors also made a certain contribution to the development of combined processes of severe plastic deformation, allowing to obtain metal with an ultrafine-grained structure. Three combined processes have been developed and investigated, which are based on the principle of equal-channel angular pressing in a matrix with parallel channels.



Figure 3 - Combined process "ECAP-drawing": 1 – wire; 2 – setting device; 3 – equal–channel step matrix; 4 – drawing die; 5 - winding drum.

Figure 3 shows the combined process "ECAP-drawing" that is an upgraded version of the ECA-broaching process. This method is a sequential combination of the process of equal-channel angular pressing and standard drawing. When implementing this process, the pointed end of the wire is set into an equal-channel step matrix, and then into a calibration fiber. After the end of the workpiece comes out of the drawing, it is secured with gripping tongs and wound onto the drum of the drawing mill [68-70]. This method of deformation makes it possible to obtain a wire with an ultrafine-grained structure and a high level of mechanical properties, the required size and shape of the cross section with a small number of deformation cycles.



Figure 4 - Experimental stand for the implementation of the combined process “rolling-ECAP”.

Figure 4 displays the combined process “rolling-ECAP” that is an upgraded version of the Extrolling process. Its key difference is that there are 2 pairs of rolls in this process. The first pair of rolls, due to the forces of contact friction, capture the workpiece and push it through the channels of an equal-channel stepped matrix. After the workpiece completely exits the channels of the matrix, it is captured by a second pair of rolls, which capture the workpiece and completely pull it out of the matrix.

In works [71-74], the studies of this process in the processing of aluminum and copper blanks are presented. It is established that due to the combined effect of two pairs of rolls and a matrix, three deformation cycles for the formation of an ultra-fine-grained structure are sufficient.



Figure 5 - Combined process "screw rolling-ECAP".

Figure 5 shows the combined process "screw rolling-ECAP" that is an upgraded version of the screw rolling process, which in itself is a rolling method that implements severe plastic deformation. The difference of this combined process is the deformation in an equal-channel matrix after the screw rolling stage. Due to the combined effect of shear during the passage of the matrix channels and torsion from the action of the rolls, the processed metal receives a high level of plastic deformation, leading to the formation of an ultrafine-grained structure in both ferrous and non-ferrous metals and alloys [75-76].

It is also possible to combine material processing processes in different aggregate states. In this case, the most well-known method is the combined process of casting, rolling and pressing [77]. In this process, the metal in the liquid state is fed to the cooled rolling rolls, which act as a crystallizer. Upon contact with the rolls, the metal hardens, is rolled and pressed through the matrix.

Conclusions

The solution of the problem of obtaining ultrafine-grained materials is difficult to provide using traditional metal forming methods. A promising direction in the development of metal forming processes is the development of shear deformations, which change the force characteristics of the process, since hardening during shear occurs less than during deformation by stretching or compression. Also, along with the implementation of shear deformations, a promising direction can be considered the development and research of methods based on the principle of alternating deformation, which will allow to process the structure and improve the quality of finished products.

When analyzing the metal forming methods, it was revealed that the implementation of severe plastic deformations allows to significantly improve the quality of the processed metal. Methods allowing to obtain blanks with an ultrafine-grained structure, are characterized by grinding the structure during deformation, as a result of which the mechanical and operational properties of the processed metal are increased. But after analyzing the main methods of obtaining UFG materials, it was concluded that due to high energy consumption, none of these methods is ready for economically justified wide industrial use. This problem can be solved by ensuring the process continuity and the possibility of long blanks deformation.

The development of combined metal forming processes, which are a combination of two or more conventional deformation processes, is the most promising direction for the development and improvement of metal forming methods. The main feature of combined processes is that the disadvantages of conventional deformation processes that are included in the combined process are reduced or completely eliminated. The considered combined deformation processes have significant technological advantages over classical discrete SPD processes.

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Ультра түйіршікті құрылымды алу үшін ауыр пластикалық деформацияны жүзеге асырудың заманауи технологияларын талдау

Мақалада ультра ұсақ түйіршікті құрылымды алу үшін ауыр пластикалық деформация (АПД) процестерін дамытудағы соңғы жетістіктерге шолу берілген. Осы процестердің негізі болып табылатын ығысу және ауыспалы деформациялардың әсер ету механизмі сипатталған. Ең танымал АКД процестері-жоғары қысымды бұралу (ЖҚБ) және тең арналы бұрыштық престеу (ТАБП)- бірқатар технологиялық кемшіліктерге байланысты экономикалық негізделген кең өнеркәсіптік қолдану үшін жарамсыз екендігі көрсетілген. Бұл мәселені деформация процесінің үздіксіздігін және ұзын дайындамалардың деформациялану мүмкіндігін қамтамасыз ету арқылы шешуге болады. Нәтижесінде, соңғы жылдары екі немесе одан да көп шартты деформация процестерінің жиынтығы болып табылатын металды құрайтын бірқатар аралас процестер. Бұл тұжырымдама металды қалыптау әдістерін әзірлеу мен жетілдірудің ең перспективалы бағыты болып табылады. Ауыр пластикалық деформацияның аралас процестерінің ұсынылған жаңа тұжырымдамалары деформацияның өнімділігін одан әрі жақсартуға бағытталған, өйткені ұсынылған барлық үш нұсқада ТАБП схемасының болуы дайындаманың бастапқы өлшемдерін айтарлықтай өзгертпестен деформациялауға мүмкіндік береді.

*Кілт сөздер:* ауыр пластикалық деформация, ультра түйіршікті құрылым, жоғары қысымды бұралу, тең арналы бұрыштық престеу, аралас процестер.

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Анализ современных технологий реализации интенсивной пластической деформации с целью получения ультрамелкозернистой структуры

В статье представлен обзор последних достижений в разработке процессов интенсивной пластической деформации (ИПД) для получения ультрамелкозернистой структуры. Описан механизм действия сдвиговых и знакопеременных деформаций, которые лежат в основе этих процессов. Показано, что наиболее известные процессы ИПД - кручение под высоким давлением (КВД) и равноканальное угловое прессование (РКУП) - не подходят для экономически обоснованного широкого промышленного применения из-за ряда технологических недостатков. Эту проблему можно решить, обеспечив непрерывность процесса деформирования и возможность деформирования длинномерных заготовок. В результате в последние годы появился ряд комбинированных процессов обработки металлов давлением, которые представляют собой комбинацию двух или более традиционных процессов деформации. Эта концепция является наиболее перспективным направлением для развития и совершенствования методов обработки металлов давлением. Предлагаемые новые концепции комбинированных процессов интенсивного пластического деформирования направлены на дальнейшее повышение эффективности деформирования, поскольку наличие схемы РКУП во всех трех предложенных вариантах позволит деформировать без существенного изменения первоначальных размеров заготовки.

*Ключевые слова:* интенсивная пластическая деформация, ультрамелкозернистая структура, кручение под высоким давлением, равноканальное угловое прессование, комбинированные процессы.

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