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METHODS FOR IMPROVING THE QUALITY OF FORGINGS AND BLANKS OBTAINED BY FORGING THROUGH INTENSIFYING SHEAR OR ALTERNATING STRAIN IN THE BULK OF DEFORMABLE METAL

The article presents methods for improving the quality of forgings and workpieces obtained by forging by intensifying shear or alternating strain in the bulk of the deformed metal. To increase the metal processing due to shear or alternating strain during forging, forging strikers are most often used, the feature of which is the geometric configuration that creates additional metal flows. Quite a lot of works from research teams from all over the world have been devoted to the problem of intensive metal processing during forging. In these publications, a number of new unique designs of strikers have been proposed and various route technologies have been considered, which can significantly increase the level of shear or alternating strain compared with the use of traditional forging tool designs.

Keywords: plastic deformation, forging, shear deformation, metal.

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1. Introduction

The technologies currently used in forging production are most often characterized by conditions of uneven metal flow, uneven stress–strain state (SSS) and, therefore, uneven structure and properties in terms of the volume of the resulting blanks. Using these technologies, manufacturers of forgings and blanks for machine-building production incur high costs for obtaining metal products of competitive quality. So, for example, upsetting and broaching during forging in flat strikers take place not only under conditions of uneven metal flow in height, but also under significant contour tensile stresses due to the presence of friction forces on the contact surface. The presence of tensile stresses during forging of low-plastic steels and alloys can lead to a violation of the continuity of the metal, and the uneven flow of the metal can contribute to the preservation of the structure of the original ingot in areas of difficult deformation [1].

The main directions of improving the processes of forging cast metal is to achieve uniformity of the stressed and strained states, the effect providing high intensity of strain at low and moderate hydrostatic pressures, by creating special schemes of the stress-strain state of the metal, improving the configuration and modernization of the forging tool. For example, using tools and deformation methods that perform additional shear and alternating strain [1, 2].

Alternating and additional shear strains in the deformable body develop due to a change in the direction of metal flow [3–5]. In traditional metal forming processes, in order to improve the quality of the metal, it is necessary to significantly change the size of the initial workpiece, which leads to significant energy and labour costs. Since casting defects inevitably occur in the volume of metal during metal smelting, mainly in the axial zones, the task is to obtain high-quality metal with welded defects at the lowest energy consumption. The technical solution to these problems is based on the implementation of shear and alternating strain in the entire volume of the deformable body [1, 2]. That is, for a high-quality processing of the cast structure, which makes it possible to obtain forgings and workpieces with a given level of mechanical properties, it is necessary to build the deformation process in such a way that sufficient shear (alternating) strain occurs throughout the deformable volume [2].

At the same time, it is known that forging is one of the most economical ways to obtain high-quality forgings and blanks for various industries. Forging provides high quality metal with stable increased ductility and strength characteristics. However, when using traditional forging technologies, an increase in the quality of forgings and blanks is provided only with a significant change in the initial dimensions of the ingot or billet, which leads to significant energy consumption. Therefore, the development of new forging technologies that allow obtaining high-quality forgings and blanks without significantly changing the original dimensions is still an urgent task.

2. Analysis of the Current State of Blacksmith Production in the World

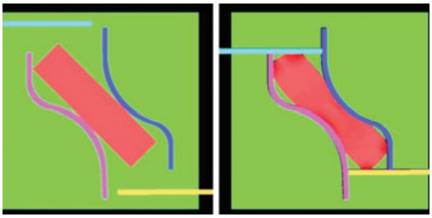
In recent years, there has been a clear trend in the development of forging in the direction of studying processes related to the so-called multidirectional forging, which is a hybrid combination of conventional free forging and hot forging [6–9]. A key feature of this process is the fact that due to the complicated metal flow, the presence of tilts at 90°, and sometimes at 45°, deformation of the entire workpiece in one cycle or with a certain number of feeds, these technologies cannot be attributed either to forging or to stamping operations. These methods of pressure treatment, based on the name, are characterized by different directions of movement of forging tools. Figure 1 shows the characteristic scheme of multidirectional forging [9].

Using such deformation scheme, it becomes possible to obtain a sufficiently complex forging shape that cannot be obtained in conventional forging operations. In addition, due to the complicated reduction scheme, the level of generated wastes in the form of burrs is significantly reduced (in some cases they are completely excluded, which is extremely difficult to do during stamping operations).

Another feature of multidirectional forging is the possibility of processing difficult-to-deform steels and alloys [10–12], which often cannot be deformed using traditional technologies. At the same time, the quality of the obtained metal structure and the level of its mechanical and physical properties can compete with similar parameters obtained after processing by methods of severe plastic deformation (SPD). The comparative analysis of these properties after such processes is devoted to a number of works [13–16].

Another promising area is the study of the strength of the forging tool in order to increase its durability and increase the overall productivity of the deformation process. These studies are aimed at increasing the wear resistance of the forging tool by controlling the content of carbon and vanadium in the tool material together with implementing the specified thickness of the nitride layer [17–19]. In addition, an important factor affecting the wear resistance of the deforming tool is its preheating technology [20].

To reduce casting defects in large forgings, such as solidification segregation, a new technology for deformation of semi-solid liquid forging has been developed [21–24]. The deformation of the semi-solid liq-



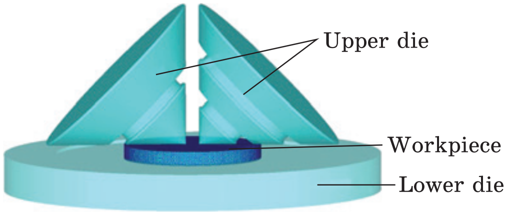


Fig. 1. Movement of the tools in multi-directional forming [9]

Fig. 2. 3*D* FE model of rotary forging with MCRs of the disc [27]

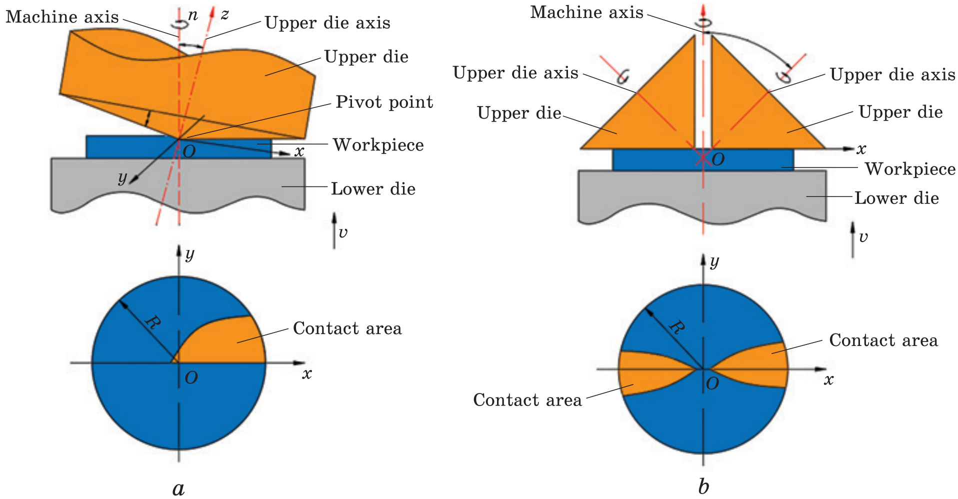


Fig. 3. Schematic diagram of rotary forging: rotary forging with single roll (*a*); rotary forging with DSRs (*b*) [29]

uid core is more uniform, the performance of the equipment is also improved. Compared to traditional forging, the new forging technology is produced directly at a high temperature without reheating for a long time, which significantly saves energy.

A new technology for forging a railway car trolley adapter, which was first developed and optimized using DEFORM-3D software, and then the feasibility of this process was tested experimentally [25]. It has been found that the use of this technology makes it possible to eliminate defects such as voids in the metal casting process, optimize the microstructure, and obtain products with good metal density.

The results of a comparative analysis of the new connecting rod forging process and the currently used technology were presented in [26]. In industry, connecting rods are currently made of extruded rods. The new forging technology involves the use of a blank in the form of a cast blank. Based on the studies conducted, it was found that the use of cast blanks reduces material waste by about 80% with respect to the technology of

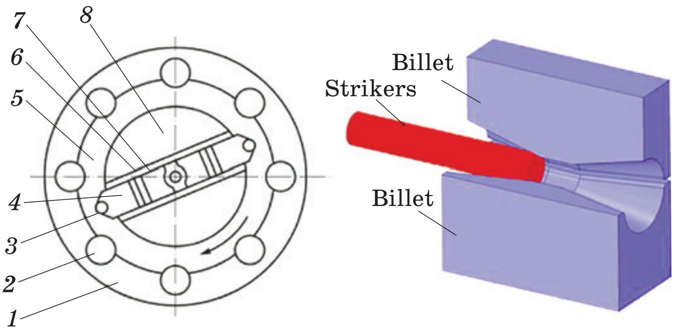


Fig. 4. Schematic of the forging unit of the two-striker machine for RF: *1* — separator, *2* — separator roll, *3* — slider roll, *4* — slider, *5* — tuning plates, *6* — striker, *7* — striker plate, and *8* — shaft [30]

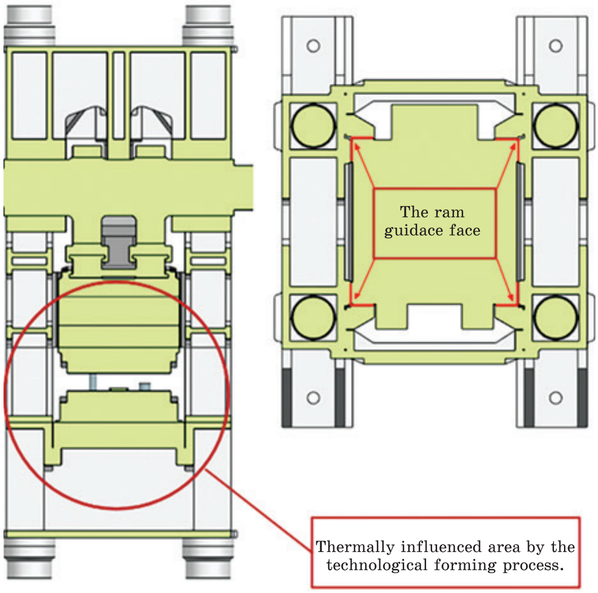


Fig. 5. The press with the description of the thermally influenced area [34]

forging from a bar and reduces the energy consumption of the process by about 75%. Both options provide forging with the intended shape and dimensions, although forging from a workpiece with a lower degree of deformation seems to be a safer option in terms of the possibility of breaking the material, as confirmed by the values of the Cockcroft–Latham criteria.

In addition to the types of forging with translational movement of the instrument, the methods of rotary forging were further developed. In particular, one of the latest deformation technologies is rotary forging with double symmetry rolls (DSR) [27–29], developed on the basis of conventional rotary forging with double symmetry rolls, which uses a pair of symmetrical conical rolls to perform continuous local plastic deformation of the workpiece under pressure (Figs. 2 and 3).

The experiment was carried out on a rotary forging press with double symmetrical rolls, the results of the experiment demonstrated that DSR rotary forging is a reliable technology for forming large diameter disks with a given thickness ratio.

In addition, rotary forging is an object of study in the development of various combined processes. For example, rotary forging is combined with radial-shear rolling [30–32] (Fig. 4), as a result of which there are

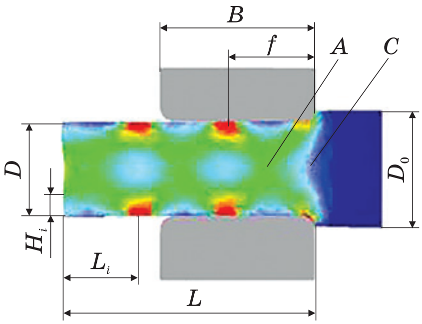


Fig. 6. Schematic drawing of the workpiece with the combination beater: L — length of deformed part of workpiece; L_i – length of deformed part of workpiece after single feed; D_0 — initial diameter of workpiece; D — final diameter of workpiece; H_i — maximum deformation penetration depth; B — striker width; f — feed value; A — axial stresses in the broaching zone, C – axial stresses at the entrance to the broaching zone [39]

prospects for industrial production of small-diameter rods with high uniformity of the fine structure; with equal-channel angular pressing [33], which leads to the formation of a mixed nano- and submicrystalline structure with high dislocation density, which provides high mechanical and functional properties.

In addition, classic types of forging do not stand aside. In particular, in-depth studies of questions related to the heat regime during forging were performed, during which thermal deformations of the main components of forging equipment were studied [34, 35] (Fig. 5). Theoretical and experimental studies were carried out to determine the value of the friction coefficient under various types of forging [36–38].

In order to eliminate the non-uniformity of the forging structure, it is necessary to ensure a uniform distribution of strain throughout its volume, and in order to eliminate axial defects, it is necessary to ensure high values of strain in the central part of the forging while providing compressive stresses. Authors of Ref. [39] developed the modes of broaching blanks with combined strikers in the conditions of non-uniform temperature field (Fig. 6).

To assess the stress state of the workpiece, the dependence of the value of the axial stress component for points A and B (Fig. 6) located on the axis of the workpiece on the thermomechanical drawing mode was investigated. The preform was initially heated to 1200 °C and then cooled to a surface temperature of 1000 °C, 900 °C, and 800 °C during forging. Based on the results of the conducted studies, it was concluded that at point. A the stiffness index of the stress state circuit takes negative values under any conditions of feeds and reductions, as well as any temperature field of the billet section, which indicates the presence of a favourable stress state of compression. At point B, when pulling the workpiece, the stiffness index of the stress state circuit also takes negative values under any conditions of supply and reduction, as well as any temperature field of the workpiece section. However, when drawing with an inhomogeneous temperature field, the stiffness index of the stress state circuit is 4 times greater than with a homogeneous one. This

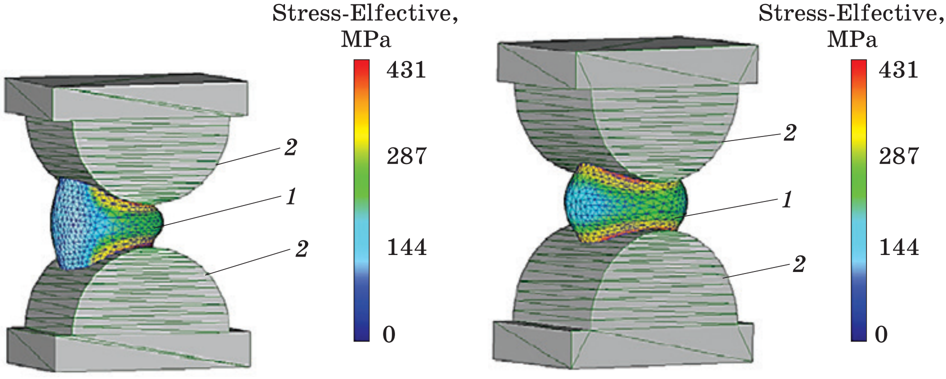


Fig. 7. Solid model of workpiece (*1*) after upsetting by convex strikers (*2*): without eccentricity $e = 0$ (*a*); with eccentricity $e = 0.25$ (*b*) [42]

is due to the presence of stiffer peripheral layers of the workpiece, which directly deform the central

Today, in the machine-building industry, preliminary profiling operations are widely used to achieve the shape of the blank to the forging configuration during forging or stamping and processing of cast metal and eliminating axial defects of the ingot [40]. Preliminary change of billet shape allows reducing contact pressure between tool and billet, to improve filling of die streams, to ensure uniform distribution of SPD, as well as to increase resistance of finish die streams.

Previously, the upsetting has already been studied by oblong convex strikers both in terms of SSS and in terms of shape change. In addition, the technology of upsetting with convex strikers was successfully applied in industry [41]. However, unlike the previous works, the authors of the work [42] conducted a study of the process of upsetting by oblong convex strikers with the eccentricity of their introduction into the end of the workpiece and without it. This work was carried out in order to expand the technological capabilities of procurement operations on crank-and-hot presses. Figure 7 shows solid models of deposited billets.

The results of studies make it possible to predict the shape change of cylindrical billets in the processes of sediment profiling with convex oblong strikers. Also in the form of regression equations there are established dependencies of change of basic parameters of deformation irregularity in height, as well as in longitudinal and transverse direction, on factors of relative degree of ε_h upsetting strain, ratio of radius of deforming tool to initial diameter of workpiece R/D_0, initial dimensions of workpiece H_0/D_0, ratio of value of load eccentricity to initial diameter of workpiece e/D_0 for samples with $H_0/D_0 = 1.0$ and 2.0.

3. Tools Implementing Effective Closure of Internal Ingot Defects

Depending on the purpose, various requirements are imposed on the products, which are determined by their operating conditions. The initial blank for forging large rolls is a forging ingot, with inherent defects in its internal structure, in the form of shrinkage shells, looseness, discontinuities and non-metallic inclusions.

Traditional forging methods that solve the problems of grinding the cast structure, shaping, improving mechanical properties are not always able to eliminate defects and the necessary level of forging quality throughout the section when forging large ingots.

Currently, much attention is paid to the development of a forging tool in order to optimize the forging process. Analysis of the conditions of deformation processing of the metal shows that the more the number of maximum shear planes can be obtained during reduction, the greater their length, the less deformation causes destruction of the cast structure.

For forging of large blanks, strikers are of greatest importance, the compression of which contributes to an increase in the directed turbulence of the metal flow throughout the section, which makes it possible to localize strain in the inner layers of the workpiece at small degrees of strain. One of the options for controlling the metal flow is the use of strikers with a profiled convex working surface. The authors have developed the design of such strikers [43], with the reduction of which an ordinary blacksmith ingot can be obtained a three-plate blank (Fig. 8).

In work [44], an analysis of the stress–strain state of round blank during crimping with combined profiled strikers was carried out, performed by the finite element method. When drawn by profiled combined strikers, the deformation zone is concentrated on the contact of the upper striker with the workpiece and spreads deep into the ingot, at the same time deformation foci are formed on the lower convexities, due to the contact of the workpiece with the protrusions and metal extrusion into the space between the convexities.

Studies show that increase of uniformity of deformation distribution and increase of deformation source area is provided at large radii of cylindrical strikers close to billet radius. Using SSS analysis, it was established that forging ingots for a three-plate billet allows us to work out the defective axial forging zone quite intensively. It has been shown that forged three-plate blanks for the manufacture of shafts are more

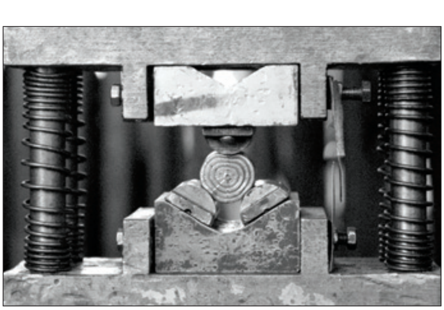


Fig. 8. Compression of workpiece with combined shaped hammers [44]

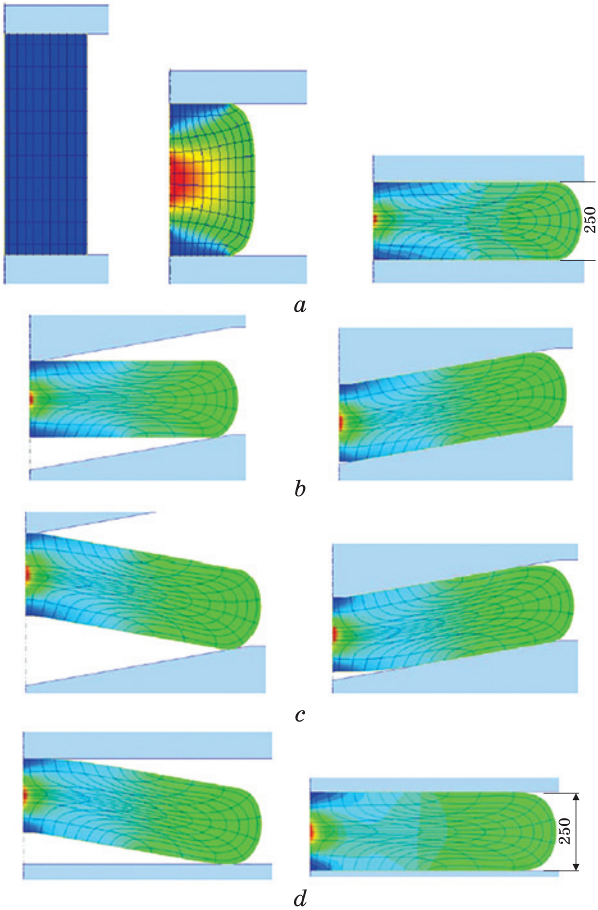


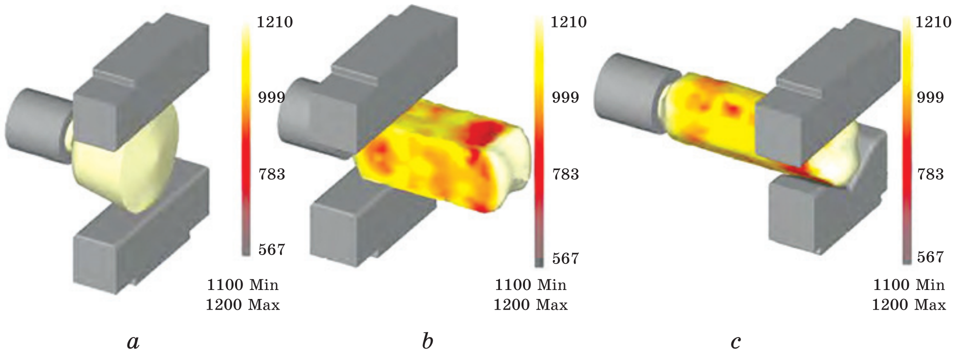
Fig. 9. Upsetting by cone plates [46]

preferable than cast ones both from the economic side (no special moulds are needed) and from the technical side (sufficient preliminary metal forging occurs). It has also been found that the profile configuration of the strikers affects the stress-strain state of the workpiece.

It is possible to increase the uniformity of the strain distribution with an unchanged bond and to ensure the elaboration of the dendritic structure while ensuring the occurrence of macroshear strain in the body of the workpiece [45].

Macroshear strain contributes to grinding grain sizes and partial reduction of liquation due to intensive shifts and movement of metal layers of the workpiece. In disk-type forgings, this effect can be achieved by alternating inversion of the deposited workpiece. To do this, you need to use a tool with the top plate convex and the bottom concave. Alternating bending will increase values of strain and uniformity of their distribution. In work [46], the strain state is studied, when convex-concave plates invert the deposited billet (Fig. 9).

Most of all, when using this method, the strain is accumulated in surface layers at a distance from the centreline from 0 to 0.75 of the workpiece radius, which makes it possible to recommend this method for use in forging parts with increased requirements for the mechanical characteristics of surface metal layers near the axis of the part. The metal on the workpiece periphery does not substantially accumulate the strain. It has also been found that the sequential upsetting method allows increasing the workpiece metal processing in the zones of difficult deformation to several times.



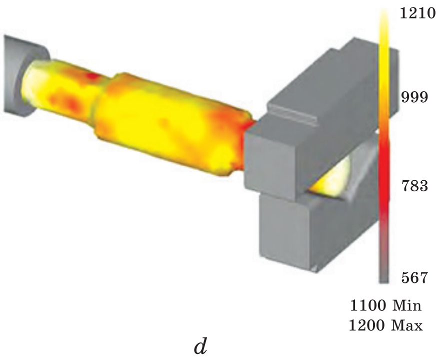


Fig. 10. Technological transitions of forging according to the new technology [46]

An effective method of axial defects closure in ingots is the use of a broaching operation, which contributes to the intensive closure of axial defects, which is not typical for an upsetting operation.

The processing of the axial zones can be improved by using convex plates for upsetting, and the conditions for eliminating defects in the cast structure can be ensured by ‘tightening’ the SSS scheme. According to one version of such technology [47], ingot heated to forging temperature is fed at press, where preliminary forging operation is performed. Upon reaching the temperature on the surface of the ingot corresponding to the lower limit of forging, the ingot with the rolled journal is placed in the lower upsetting plate and settled with the help of conical strikers. The conical upsetting plate acts mainly on the axial region of the ingot, cooled surfaces, the layers of which have a significant lateral support. During these operations, further cooling of the trunnion occurs. In this regard, the deformation resistance of the trunnion metal becomes significantly higher than that of the inner layers. Therefore, in the subsequent upsetting, the trunnion plays the role of a tool that has a concentrated force effect on the axial zone of the ingot.

The new process under investigation [48] involves the use of a shortened ingot weighing 25000 kg with a ratio $H/D = 0.7$ with a taper on two sides of 20%, while the yield factor is 83% (Fig. 10, *a*). The new technological process consists of the following operations: heating of the

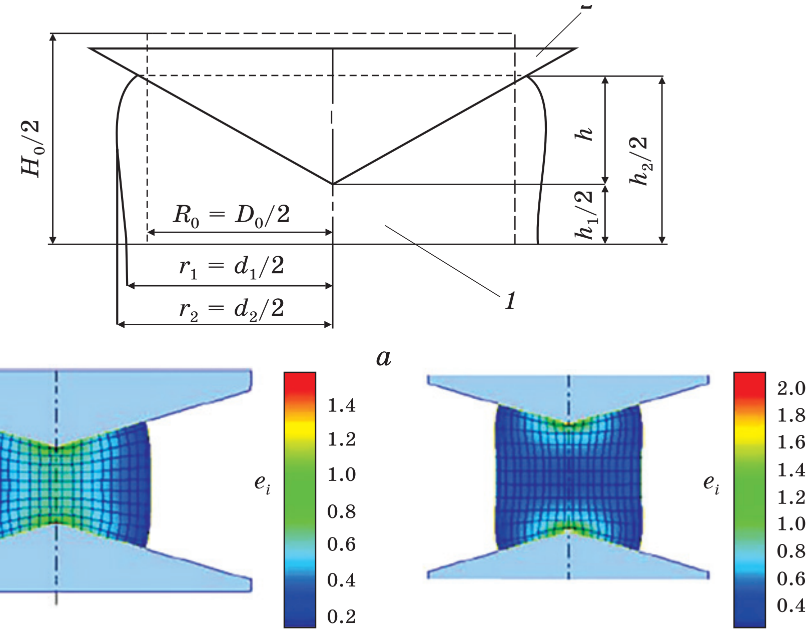


Fig. 11. Billet upsetting by conical plates: *a* — diagram for measuring a workpiece; *b* and *c* — models of upset billets [50]; *1* — workpiece with final dimensions h_1, h_2, r_1, r_2; *2* — upper cone sedimentation plate; e_i — deformation intensity (scale)

ingot, drawing with flat strikers to the square section of the 1010×1010 (Fig. 10, *b*), through the octahedron, we pass to a circle with a diameter of 1010 mm (Fig. 10, *c*), after which they spotted and pulled the bottom and profitable forging necks (Fig. 10, *d*).

The proposed technological process excludes the use of such operations as trunnion tightening and billing, ingot sediment and heating associated with these operations. All this reduces the labour intensity and energy intensity of the process by an average of 25–35%, increases the productivity of forging processes. The results obtained show that the implementation of a new technological process of forging a shortened ingot without precipitation is possible in one heating. The average forging temperature at the end of forging does not decrease below the minimum limit of the forging temperature range (Fig. 10, *d*). The exclusion of the precipitation operation and its replacement by broaching with the use of a shortened ingot can lead to a decrease in the quality of forgings, due to a decrease in the forging and, as a result, a decrease in the processing of the cast ingot structure from a lesser degree of metal deformation. Therefore, it is necessary to compare the two technological processes of forging according to the basic and new technology in order to obtain a given processing of the structure (quality of forging).

In Ref. [49], the goal is to determine the forging scheme using the broaching operation, which ensures a high and uniform distribution of strain and closed axial defects. By the finite element method, forging schemes with cutout and flat strikers were determined, providing a state of uneven all-round compression in the axial zone, which ensures the closure of an axial defect with a diameter of 10% of the diameter of the workpiece when compressed by 25 and 30%, respectively. Forging with flat strikers provides a more uniform distribution of strain over the section of the workpiece than forging with cutout strikers. At the same time, the level of accumulated strain in the peripheral zone of the workpiece is 1 unit higher than in the case of broaching with cutout strikers. The central layers have the same degree of accumulated strain, but for flat strikers the area of the deformed metal is larger. The scheme of forging with flat strikers provides the possibility of accumulation of strain in the body of the workpiece without a significant change in the cross-sectional area.

Upsetting by conical plates (Fig. 11) [50] with certain characteristics of their profile and contact friction conditions leads to a decrease in the unevenness of strain of the workpiece, which is used in known methods for determining the coefficient of contact friction when choosing an effective technological lubricant.

In the work [50], the regularities of the shape change of blanks during precipitation by conical plates were established, which allow determining the dimensions of the profiled billet after deformation, depending on its initial dimensions, the amount of compression and the taper of the sedimentary plates. It was also revealed that the rheological properties of the materials of the workpieces have a significant impact on the uneven strain in height of the deposited semi-finished products.

There are known methods of forging large forgings such as shafts in cutout and combined strikers. However, forging in these strikers is characterized by an uneven distribution of deformation over the forging section.

In order to increase the uniformity of the distribution of strain across the section of the workpiece and increase the intensity of strain due to the occurrence of additional shear strain, a forging tool was proposed that contains upper and lower cutout strikers [51]. Deformation of workpieces by cutout strikers of this design contributes to the occurrence of additional shear strain along the forging section. If, when compressing the workpiece with flat strikers, the compression limiter is a transition coefficient equal to 2.5, then, when broaching high-plastic steels under cutout strikers, the degree of compression is limited by the size of the strikers.

With a small alignment, there is a possibility of metal leaking out of the cavity of the strikers, which, during subsequent crimping, can

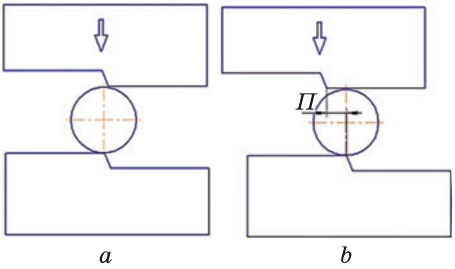


Fig. 12. Diagram of plastic deformation of workpiece by stepped strikers with zero overlap (*a*) and positive overlap (*b*); *n* — overlap value of the upper steps on both strikers (*i.e.*, in the first figure — zero overlap, in the second figure — positive overlap) [53]

lead to the formation of 'clamp' type defects. With a large alignment, the degree of compression is limited by the closure of the upper striker with the lower one.

The maximum possible compression of the sample will occur with such a diameter of the workpiece when, at the time of closing the strikers in the middle part of the deformable section, the working space of the striker is completely filled with metal, *i.e.*, when the maximum width of the deformable workpiece becomes equal to the width of the cut-out striker. For different feeds, it is obvious and the maximum compression will be different.

The provision of intensive shear deformations during pressure treatment allows obtaining high mechanical properties of the workpiece. Many technologies allow implementing this SSS scheme [52]. The effectiveness of these methods consists in an increased level of mechanical properties of the finished product with a decrease in the value of reduction.

For example, mathematical modelling of the deformation process of the workpiece by stepped strikers with zero and positive overlap was carried out (Fig. 12) [53]. As a result of modelling, the intensity distribution fields of logarithmic and shear strains in the cross section of the workpiece at various stages of deformation were obtained.

By the method of combined plastic deformation with stepped strikers, it is possible to provide intense shear strain in the workpiece. With an increase in the height of the striker ledge and the compression stroke, the level of shear deformation in the workpiece increases. Compression by stepped strikers causes an intense shift not along the entire section of the workpiece, but only along the line passing through the tops of the ledges of the upper and lower strikers. An increase in overlap does not affect the level of shear strain in the workpiece, but at the same time the intensity of strain increases, which indicates a more intense metal flow in the longitudinal direction. It was also found that the quality of shaping is affected by the size of the striker ledge and the compression of the workpiece. With greater compression by strikers with a large ledge, a defect in the form of a clamp is observed in the cross section of the work-

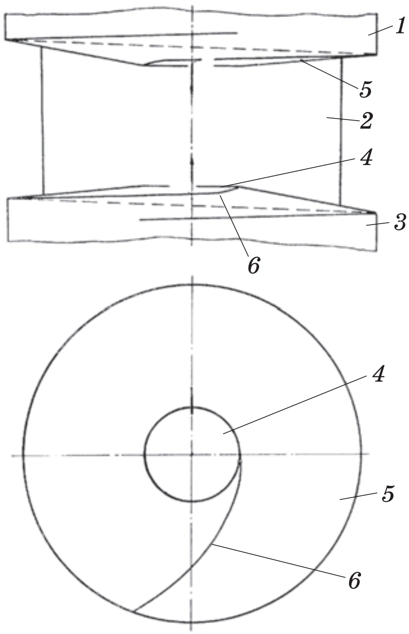


Fig. 13. Upsetting-torsion tool: *1* — upper deforming tool; *2* — is a deformable blank; *3* — a lower deforming tool; *4* — a central planar surface; *5* — working surface of the deforming tool; *6* — joint line of screw surfaces [58]

piece. The presence of overlap in the strikers negatively affects the quality of the shaping of the workpiece when it is compressed after turning, *i.e.*, it is necessary to ensure its minimum value.

The use of step strikers during forging ensures the required quality with minimal extraction [54]. The required quality of the workpieces is ensured by the development of large shear strain due to shape change, in which there is no or weakly expressed predominant metal flow in one direction. For identical hoods, stepped strikers provide an increase in the intensity of shear strain in the axial zone of the workpiece with a significant decrease in the unevenness of strain along the height of the workpiece. Since there is an eccentricity of loading when using step strikers, it is necessary to modernize the equipment.

The torsion of the workpiece also has a positive effect on its quality. When broaching, the twisting of the workpiece can be performed in a special tool with a crossing working surface [55]. The difference between this tool and the existing one [56] is that a gap z provided between the crossing inserts of the lower (*2* and *2¢*) and upper (*1* and *1¢*) strikers in order to avoid snacking of the workpiece. Forging in these strikers acquires a spiral shape, which allows it to be used for subsequent precipitation in order to twist the longitudinal fibres and reduce the upsetting force. The increase in mechanical characteristics, improvement of the macro- and microstructure of the metal of the workpieces is provided with the reduction 1.2–1.3. The same quality of the workpieces on flat strikers is provided with the reduction 2.5–3.0.

When determining the optimal parameters of deformation in crossing strikers, it was found that supplementing the design of these strikers with inserts of various shapes makes it possible to increase their efficiency due to the emergence of additional shear systems in the volume of the deformed workpiece.

When forging large-sized workpieces, it is difficult to ensure deep penetration of the deformation zone to the central layers of the ingot.

To do this, it is necessary to use special forging tools that ensure a uniform distribution of strain throughout the entire volume of the workpiece. The use of special tools also ensures the closure of internal defects of the ingot.

In Ref. [57], a method of deformation is proposed, including broaching with twisting of the workpiece to implement additional shifts in the deformation zone. Similarly, a method for forging forgings with flat strikers is proposed, in which shear and compression strains are simultaneously carried out. Due to this, the processing of the cast metal structure is improved.

The authors of [58] propose a combined scheme of deformation 'upsetting–torsion', in which the operation of upsetting with torsion is provided in this tool (Fig. 13). The peripheral zones of the working surfaces of the strikers are made along a helical plane with the same direction of twisting to improve the deformation conditions.

When draining, the screw-working surface of the tool creates at each point of contact with the workpiece the force acting in a horizontal plane perpendicular to the flow of metal in the diametric direction. The resulting forces create a torque, in addition, the direction of twisting of the screw surface of both strikers is the same, and therefore, when installed opposite each other and the subsequent draft, its ends twist in different directions. Deformation on this tool allows getting a uniform processing of the structure of the workpiece. In addition to this, the contact friction forces lead to a decrease in the deformation force.

In Ref. [59], intensive deformation of the initial structure of the workpiece is carried out and energy consumption is reduced by reducing the required deformation force. This is achieved by adhering to the end surfaces of the workpiece during upsetting; thereby the volumes of metal are displaced by protrusions in both radial and tangential directions. The displacement of large volumes in one direction is achieved by the arrangement of the working faces on the same plate. Displacement of metal volumes leads to the appearance of a moment of forces tending to twist the workpiece. As a result, new shear planes appear in the metal.

In order to improve the quality of the metal due to the processing of the cast structure, it is necessary to use tools or devices with a complex configuration with additional movements of the working surfaces. The implementation of the forging operation in such tools will ensure an increase in the mechanical properties of the metal due to the implementation of intense shear strain in the volume of the workpiece.

4. Forging Technologies Allowing Intensifying Shear or Alternating Strain in the Bulk of Deformable Metal

For more than a decade, almost the only way to obtain large forgings and blanks for the manufacture of machine parts and equipment is forging. Forging of both ferrous and non-ferrous metals and alloys in the hot state, in addition to giving the ingot or billet a given shape and size, is also used to eliminate various defects in metallurgical production. However, until recently, in the existing blacksmith shops, the technological processes of forging ingots and blanks are based on the use of traditional forging tools and inefficient deformation modes. Therefore, these forging processes are characterized by low quality of the forgings obtained, low yield coefficients of suitable forgings, large forging coefficients, and this in turn requires significant energy and labour costs. Therefore, obtaining high-quality forgings and blanks with a fine-grained structure and without defects by new methods of forging from ingots of conventional smelting with a significant reduction in energy and labour costs is relevant and economically advantageous.

It has long been proven that the most effective way to improve the quality of forgings or workpieces obtained by forging is the intensification of shear or alternating strain in the deformable metal. This is primarily due to the fact that in this case it is possible to better work out the cast structure and obtain forgings and blanks with a fine-grained structure with less change in the initial dimensions of ingots or blanks, *i.e.*, with less forging. In addition, it is also known from the work [60] that when developing the design of a forging tool that implements shear strain, the fact should be taken into account that the tool, in which the mechanical deformation scheme is implemented, namely, pure shear is most preferable. Since in this case, when deforming in such a forging tool, a minimum amount of energy is spent on deformation, maximum and uniform processing of the metal structure along the cross-section of the deformable workpiece (ingot) is achieved, fine-grained structure, specified physical and mechanical properties, brewing of internal defects are ensured. Deviation in the implementation of forging operations in a certain tool from the mechanical deformation scheme, namely, a net shift leads to additional energy costs and can be justified only if other technological advantages of forging in this tool are obtained.

At the moment, many different methods of forging ferrous and non-ferrous metals and alloys are known, including for obtaining forgings of rectangular cross-section, as well as forgings of the type of plates and plates that allow for the implementation of intense shear strain in the deformable metal. In these forging processes, the intensification of shear or alternating strain can be achieved due to the following factors:

changes in the configuration of forging tools or a complex application of the load acting on the metal.

Let us consider the most effective methods of forging rectangular cross-section forgings at the moment and tools for their implementation, ensuring the implementation of shear and alternating strain in the process of metal deformation.

The simplest and most effective way to work out the cast metal structure to obtain a fine-grained structure and close internal defects, and if they are clean of impurities, then welding is a comprehensive forging, during which the workpieces are deformed alternately in three mutually perpendicular directions. The study of the strain state of the metal during the implementation of this deformation scheme proved that in the volume of metal forgings formed by this method in just a few cycles, it is possible to localize significant shear strain throughout the entire volume of the deformed workpiece [61].

In addition to the above method of deformation, it is possible to achieve the implementation of additional shear strain by developing effective deformation modes, combining various forging operations or various standard forging tools, for example, flat strikers and cutout or combined strikers.

Therefore, for example, it is known that the basic scheme of forging ingots of various cross-sections and blanks of round, square cross-section is the forging scheme: circle–circle. The authors of the work [62] proposed an improved deformation scheme, which consists in the fact that with each single compression of the workpiece sections, two compression schemes are implemented, namely, two strikers and four strikers, leading to an asymmetric displacement of metal in two mutually perpendicular directions. This deformation scheme ensures the twisting of the metal fibres relative to the longitudinal axis of the forging, *i.e.*, contribute to the creation of additional macro-shear strain in the cross section of the workpiece. Moreover, this, accordingly, makes it possible to improve the study of the microstructure of the metal at lower values of the reduction coefficient and reduce the heterogeneity of the mechanical properties of the metal along the cross section in the longitudinal direction.

In Ref. [63], a method of forging ingots is proposed, which consists in pre-stretched ingot in flat strikers before forming a rectangular-shaped forging, followed by broaching in cutout strikers. And in Ref. [64], a method of forging ingots was proposed, which consists in deforming the ingot first by single compression in strikers with a cut-out angle in the range of 135–150°, and then in strikers with a cut-out angle of 90°. These forging methods make it possible to improve the quality of forgings by developing additional shear strain in the central zone of the ingot.

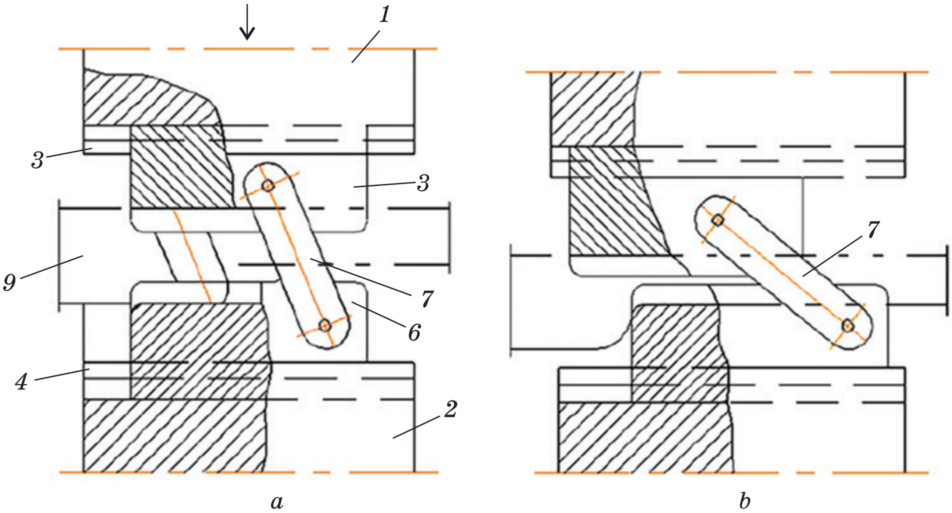


Fig. 14. Longitudinal shear forging tool diagram: *1* — upper striker, *2* — lower striker, *3* — guide relative to the upper striker, *4* — guide relative to the lower striker, *5* and *6* — working inserts, *7* — crank, *8* — hinge, *9* — blank [69]

As known, when forging in flat strikers with a rectilinear feed front, the maximum deformations are distributed over the forging cross, and the minimum in areas of difficult deformation. Therefore, the authors of [65] proposed a technology for forging forgings in flat strikers with an indirect feed front, which reduces the unevenness of deformation, as well as the development of additional shear strain in the volume of the deformable metal.

One of the most effective ways to obtain high-quality forgings with a fine-grained structure are forging methods in which complex tool movement is carried out. Thus, in the works [66, 67], methods were proposed for carrying out a forging operation, namely, sediment in flat plates, which made it possible to improve the quality of processing the cast metal structure by creating shear strain simultaneously with compression strain. To do this, simultaneously with the application of the deformation force along the forging axis, forces are reciprocally applied from its ends in mutually intersecting directions in a plane perpendicular to the direction of the deformation force.

In Ref. [68], authors proposed a tool for forging metal with a longitudinal shift of the workpiece [68]. The tool shown in Fig. 14 makes it possible to increase the productivity of work and improve the quality of metal processing. In the initial position (Fig. 14, *a*), the strikers are divorced and the processed product is fed between them. When the slider moves down, the strikers approach, as a result of which the cranks *7* rotate around their hinges *8* and move the working inserts *5* and *6*

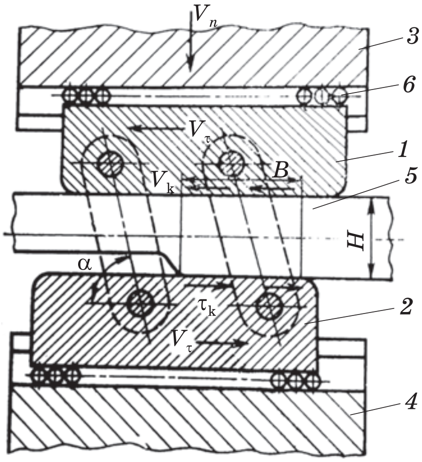


Fig. 15. Longitudinal shear forging-broaching process diagram: *1* — segment of the upper, striker moving horizontally; *2* — segment of the lower striker moving horizontally; *3* — segment of the upper striker moving vertically; *4* — segment of the lower striker moving vertically; *5* — blank; and *6* — rotating rollers [69]

along the guides *3* and *4* relative to the upper *1* and lower *2* strikers in mutually opposite directions. Due to this, the working inserts *5* and *6* act on the processed material both in the normal and tangential directions, causing both its upsetting and displacement due to oppositely directed contact friction forces from the upper and lower strikers [69].

After reaching the set compression value (Fig. 14, *b*), the upper striker rises together with the press slider, the cranks *7* turn in the opposite direction, and the working inserts return to their original position. Then, the material is fed again and, if necessary, it's edging.

Authors of Ref. [70] carried out studies of the forging-broaching process with longitudinal shear (Fig. 15). The greatest interest is the analysis of the influence of the parameter m (the ratio of the tangential and normal velocity of the strikers at any given time) on the nature of the distribution of stresses and strains in the plastic region. When a longitudinal shift is applied, the main flow occurs in the direction of the axis, and the broadening of the metal is insignificant.

Studies have shown that when forging high strips, longitudinal shear leads to a favourable distribution of stresses and strains, which contributes to high-quality forging of the material and eliminates axial destruction, while the energy performance of the process deteriorates. These features are determined by the relatively weak influence of contact friction for high bands and the restructuring of the deformation focus due to the shift of the strikers.

The analysis of this forging scheme has shown that compression with longitudinal shear is most appropriate when feeding $B/H = 1$ and with a velocity ratio of $m = 1$, when uniform processing of the material is achieved and the risk of destruction is reduced. This case is also optimal in terms of the energy intensity of the process.

In Ref. [71], authors also investigated the forging process in combined strikers. They investigated the process of closing the internal voids of the workpiece when forging with combined strikers: upper cutout, lower flat [71].

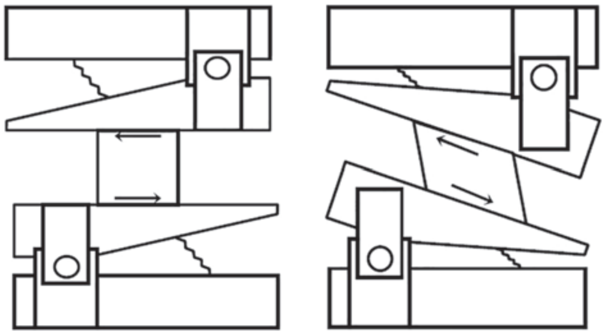


Fig. 16. Diagram of workpieces deformation in hammers with elastic elements, where *a* (*b*) — the first (second) transition [75]

In their work, it is noted that broaching is the most important forging operation for closing internal defects of metallurgical origin of the workpiece. It is shown that when using combined strikers, brewing of the internal defect of the workpiece in the form of a through hole occurs more efficiently than when forging with flat strikers.

Much attention is also paid to the study of special designs of strikers, their influence on forging parameters. In Ref. [72], authors carried out simulation of the operation of broaching with strikers of a special shape, namely, cutout radius and trapezoidal. It is established that the cutout trapezoidal strikers provide a more intensive elongation of the workpiece and a lower broaching force. The authors found that the greatest uniformity of the distribution of the strain intensity over the entire volume of the workpiece is obtained when forging with radial cutout strikers. However, they note that from the point of view of economic and qualitative indicators, forging with trapezoidal strikers is more preferable.

In Ref. [73], authors conducted a study of the effect of the relative feed of the workpiece on the strain state of the workpiece during forging with profiled strikers. The strikers have a flat shape with bevels on both sides. They found that, for the greatest uniformity of the distribution of deformations and stresses in the workpiece, the strikers should have a bevel equal to 60°; forging should be carried out with a single compression of 25% and a relative feed of 0.4. They found that the angle of the bevel of the strikers affects such forging parameters as the relative elongation of the workpiece, the strength of the broach and the heterogeneity of the distribution of strain in the workpiece.

In Ref. [74], authors performed a simulation of the forging process of a workpiece with defects of metallurgical origin in the form of discontinuities. The process of forging a cylindrical workpiece with holes located in the central part of the workpiece and at different distances from it was investigated. The study of forging in strikers of various configurations: cutout radial asymmetrical and cutout trapezoidal was carried out. Based on the theoretical and experimental studies carried out, it was found that the use of profiled strikers helps to reduce internal defects in the workpiece in the form of discontinuities and reduce the heterogeneity of the distribution of strain along the section of the workpiece. It is noted that these strikers have an advantage over the flat, cutout and combined ones traditionally used at Polish enterprises.

In Ref. [75], another forging tool was proposed for forging forgings of the type of plates and plates, namely strikers with elastic elements, which are also based on the complex movement of the tool (Fig. 16). The tool works as follows. When the press slider moves down, the upper striker presses on the workpiece, since at the initial moment of compression, the deformation force is equal to the stiffness of the elastic elements, then the usual draft of the workpiece occurs first. With a gradual increase in the cross-sectional area of the workpiece, the deformation force begins to grow and as a result of counteraction from the workpiece, the elastic elements provided in the strikers are compressed, and the working inserts move obliquely in the direction of the upper and lower flat parts of the strikers, respectively. Due to this, one part of the workpiece is shifted relative to the other. After reaching the set compression value, the upper striker rises together with the press slider, and the elastic elements return the working insert to its original position. Then the workpiece is fed and compressed in the same way. After pulling the entire workpiece, it rotates around its axis by 180° and straightens in the same strikers. Experimental studies conducted during pilot testing have shown that the development of significant alternating strain in the entire volume of the deformed body when forging workpieces in strikers with elastic elements makes it possible to better work out the cast structure of the metal to obtain fine equiaxed grain throughout the volume of the deformed workpiece without significantly changing its original dimensions, and to obtain forgings with better mechanical properties compared with forgings forged according to the current technology in flat strikers [75].

The authors of the work [76] proposed a forging tool for forging forgings of rectangular cross-section, containing upper and lower strikers equipped with elastic elements with a convex working surface. The deformation of the workpiece in this forging tool is carried out according to the following scheme: the workpiece is installed between the upper and lower striker and deformed by curvilineal convex working surfaces, which at the end of the tool stroke take a flat working surface. At the initial stage, deformation by curvilineal convex working surfaces allows to localize the strain in the surface layers of the workpiece. In the process of deformation under the influence of bending of curvilineal convex working surfaces, a scheme of alternating strain is implemented in the end parts of the workpiece.

In addition to giving the forging tool a complex movement, for the realization of shear strain in deformed metal, it is possible to achieve

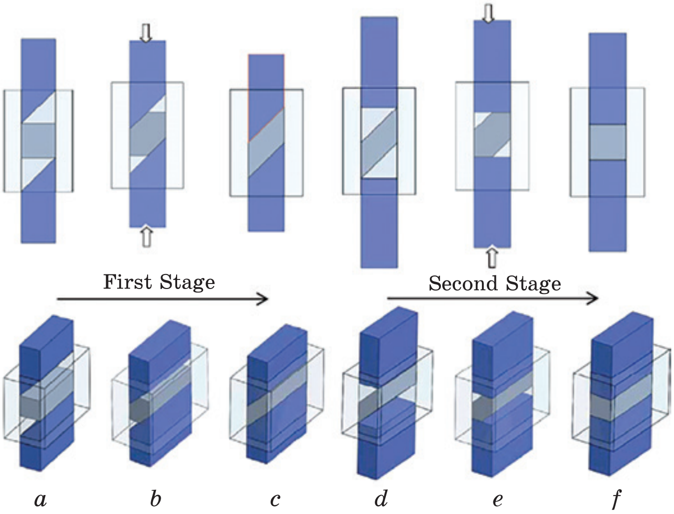


Fig. 17. Schematic of RF process [77]

the same effect by implementing cyclic forging, proposed by the authors of [77]. A schematic representation of the process is shown in Fig. 17, which shows that the process consists of two stages. During the first stage, the cross section of the workpiece is gradually deformed to the shape of a parallelogram from the initial square. Then, in the second stage, the workpiece is deformed in such a way that it turns out to return the initial shape of the cross-section in the form of a square. This process can be repeated as many times as necessary to obtain the required grain size without changing the initial cross-section of the workpiece.

The most common method of achieving the development of additional shear or alternating strain in the volume of the deformed metal when forging workpieces of various geometric shapes, including rectangular, is the use of tools of various geometric shapes in the process of forging broaching. For example, in the work [78], the authors proposed strikers as a tool for forging, the working surface of which has protrusions and depressions. In this case, the protrusions of one striker are located against the depression of the other. In addition, in the work [79], an instrument is considered in which the protrusions of one striker are shifted against the other by a quarter of a step. When forging broaching in special strikers proposed in [80], it is possible to process long blanks in conditions of intense alternating strain. According to this technology, the ingot is crimped in two stages, first in profile strikers, then in flat strikers. In profile strikers, protrusions and recesses are formed on the workpiece. On smooth strikers, the workpiece is smooth and acquires the same dimensions. In the profile section, cylindrical protrusions displace metal particles into the recesses on the strikers. On a flat section of the striker, metal particles from the protrusions on the workpiece move into the recesses. This is how intensive alternating strain is carried out. From the work [81], a tool is known that has a triangular cut-out on the side surfaces, providing an intensive metal flow not only in the longitudinal, but also in the transverse direction, and from the work [82], a cut-out striker with a wave-shaped relief working surface is known, the wave front of which is located parallel to the broach axis. Forging in the above-listed strikers provides intensification of shear strain, both in different layers of the workpiece and in different directions.

As noted above, much attention is currently being paid to the development of new forging tools that allow for the implementation of severe plastic deformation in the entire volume of the deformable metal. At the same time, the analysis of the conditions of deformation working of the metal shows that the greater the number of planes of maximum shear can be obtained during compression, the greater their length, the less deformation the destruction of the cast structure occurs. Therefore, for forging large forgings, strikers acquire the greatest importance, the compression of which contributes to an increase in the directional turbulence of the metal flow throughout the cross section, which allows for small degrees of strain to localize it in the inner layers of the workpiece. One of the options for regulating the flow of metal is the use of strikers with a profile convex working surface. The authors have developed the design of such bikes [82], when compressing an ordinary forge ingot; a three-petalled billet can be obtained.

5. Conclusions

The article highlights the main forging methods and control factors of the stress–strain state of the workpiece in the forging processes of large forgings. It is established that much attention is paid to the study of the processes of forging workpieces with tools of various shapes, but, in most cases, there are no specific recommendations for calculating the size of the tool for certain forging conditions, forging modes. In addition, little attention is paid in the literature to forging ingots of special configurations due to their low distribution in production.

Studies of the complex kinematics of tool movement, its effect on the SSS of the workpiece, when forging is large, forgings are few due to the complexity of its implementation in practice. Thus, only radial forging in special machines or devices installed on a conventional hydraulic forging press has found widespread use.

Great interest has new forging schemes with complex kinematics of tool movement of complex configuration, which can be implemented in special dies or on specialized equipment, which can also give impetus to the creation of a new type of equipment.

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МЕТОДИ ПОЛІПШЕННЯ ЯКОСТИ ПОКОВОК І ЗАГОТОВОК, ОДЕРЖАНИХ КУВАННЯМ, ШЛЯХОМ ІНТЕНСИФІКАЦІЇ ЗСУВНОЇ АБО ЗНАКОЗМІННОЇ ДЕФОРМАЦІЇ В ОБ'ЄМІ МЕТАЛУ, ЩО ДЕФОРМУЄТЬСЯ

У статті наведено методи поліпшення якости поковок і заготовок, одержуваних куванням, шляхом інтенсифікації зсувної чи то знакозмінної деформації в об'ємі металу, що деформується. Для підвищення опрацювання металу за рахунок зсувних або знакозмінних деформацій під час кування найчастіше використовуються ковальські бойки, особливістю яких є геометрична конфіґурація, що створює додаткові потоки течії металу. Проблемі інтенсивного опрацювання металу під час кування присвячено достатньо багато робіт від наукових колективів з усього світу. В цих публікаціях було запропоновано ряд нових унікальних конструкцій бойків і розглянуто різні технології, що уможливлюють істотне поліпшення рівня зсувних або знакозмінних деформацій порівняно з використанням традиційних конструкцій ковальського інструменту.

Ключові слова: пластична деформація, ковка, зсувна деформація, метал.