Obtaining conical shells by forging is an important and relevant task in energy and heavy engineering. Existing processes of their manufacture come down to simplifying the configuration of such billets. The result is the increased material's consumption while the internal fiber is cut during machining, which also leads to a decrease in mechanical properties. A new forging technique necessitated a study into the shape change of the billet and the distribution of deformations in the process of rolling. A finite-element method was used to investigate the process of rolling out the step hollow billets. Based on the study results, the forging's taper was established, obtained during the forging process. A research procedure involving the finite-element method was devised to study the operation of conical shells' rolling, which made it possible to determine a change in the shape and size of a hollow forging when rolled out by a step tool. A parameter has been proposed to quantify the formation of taper in the process of rolling a billet with a flange. Based on the study results, a step-wise distribution of the intensity of logarithmic deformities in the body of a forging was established when conical shells were rolled out. It was found that the step deformation leads to an increase in the uneven distribution of deformations on the part of the protrusion and ledge. Maximum deformations of 1.0...1.2 occur at the inner and outer surfaces of the step billet's protrusion. Dependences of the shape change in a step billet for the investigated ratios of sizes and rolling modes have been established. It was found that the maximum taper is obtained at a deformation degree of 15 %. It was determined that the degree of compression in the ledge and protrusion is leveled after 3 deformation runs of the step billet

Keywords: forging, rolling, taper, conical shell, ring, hollow forging, step striker

UDC 621.736

DOI: 10.15587/1729-4061.2020.216523

DETERMINING THE DEFORMED STATE IN THE PROCESS OF ROLLING CONICAL SHELLS WITH A FLANGE

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Received date 11.09.2020
Accepted date 03.11.2020
Published date 11.12.2020

1. Introduction

The main reserve in the development of heavy and energy engineering is the improvement of resource-intensive manufacturing processes to forge especially responsible forgings (bodies of nuclear reactors, etc.). This necessitates studying and devising new manufacturing processes that could improve the mechanical properties of articles. The main issue related to the advancement of machine engineering is to design improved energy-saving processes that would contribute to better quality and decrease the consumption of metal and energy. Achieving the set goals will make it possible to practically implement the resource-saving manufacturing process to forge billets for the manufacture of reactor bodies [1]. The optimization parameters are the following: high mechanical properties and competitive cost of billets to produce parts for particularly responsible purposes. Devising scientifically-substantiated recommendations to improve the mechanical properties and reduce the cost of large billets implies the undertaking of appropriate research, which could form the basis for designing new forging manufacturing processes and deforming tools. That would lead to devising an integrated approach that could take into consideration the basic technological chain in the forging of reactor bodies' billets: receiving ingots, heating, and deforming them. An important scientific and technical task in energy engineering is to obtain parts of the conical shape, including step-shaped. Receiving forgings of similar geometry would make it possible not to cut the structure of a billet during machining, as well as reduce the consumption of metal. This would require modeling the stressed-deformed state of a billet when implementing a new method to roll the step hollow forgings.

A relevant scientific and technical task in the production of large billets for energy and heavy engineering is to obtain conical forks with a flange, which are close to the shape and size of a part. This would expand the technological capabilities of forging, preventing cutting the fibrous structure of a part's metal and reducing the consumption of metal during machining.

2. Literature review and problem statement

Existing manufacturing processes to forge ingots under pressure imply the use of an energy-intensive upsetting operation [2]. When making hollow forgings, this operation is required to increase the area of the cross-section of a billet before piercing [3] during the fabrication of shells. However, at piercing, part of the metal is wasted, which leads to unnecessary metal consumption. It is possible not to apply a piercing operation if hollow ingots are used. In this case, a rod or a pipe is inserted into the middle of the mold to form a future hole. There are known techniques involving a cooling pallet [4, 5], which contribute to improving the quality of the original billets. However, the ingots should be cast from below. This, in turn, complicates the mold design.

Paper [6] found that casting an ingot using a siphoned technique through two inlet holes and cooling with a double pipe and sand produces better results than when three and four holes with standard cooling are used. Based on the modeling results, the optimal shapes of molds were designed for hollow ingots; two ingots weighing 37 and 60 tons were cast. The manufactured shells had an outer diameter of 1,750 mm and 3,000 mm, the number of defects was minimal. However, the analysis of the experience of using a conventional ingot and a hollow one made it possible to establish that in the manufacture of large hollow forgings using a conventional ingot all defects of the axial part cannot be eliminated applying a piercing operation.

It is stated in work [7] that defects were found at the inside surface of the forging made from a conventional ingot. It was possible to avoid these defects after the engineers applied a hollow ingot. That ingot had a displaced crystallization center closer to the wall; after manufacturing, the part had no defects at the inner surface of the ingot. Owing to improvements, the «whiskers» defects were located in the middle part of the wall of the hollow billet, which contributed to its reduction during forging. However, the cited work does not report results regarding the mechanical properties of forged shells, which is an important criterion when choosing a new technique to forge billets for particularly responsible purposes.

Paper [8] outlines the main characteristics of the process of centrifugal electro-slag smelting of hollow ingots ∅600/350 mm, N=290 mm, weighing 0.4 tons, from the structural steel 20KH2N4A. The chemical composition, structure, and mechanical properties of these ingots are described. It was established that these ingots are characterized by high chemical and physical homogeneity, a high level of mechanical properties and isotropy, and can be used in both cast and deformed states for rolled rings and shells. It was found that those ingots can be used without prior machining, which simplifies the manufacturing process and reduces the cost of rolled rings. However, the cited paper does not specify the possibility of using a given technology to produce large ingots weighing more than 100 tons and the possibility of forging large shells of the conical shape from those ingots. This, in turn, requires special research into large forgings.

Studies [9, 10] report the results of implementing the technology of electroslag remelting (ECP) to obtain hollow billets. Based on the study results, the authors determined the possibility and feasibility of using hollow ESP billets in a cast state or with an optimized degree of articles' deformability. However, the cited studies do not specify the possibility of using these ingots for articles with a profiled external surface.

Paper [11] states that it is possible to expand the size range of hollow forgings at constant tool parameters by using a special device. In the device, a mandrel is rigidly connected by means of rods to a movable crosshead of the press and is located with its longitudinal axis in the plane of the striker cut. At the same time, the striker is fixed on the table of the press. A lower cutout striker is attached to the press's table, located with its larger side parallel to the longitudinal axis of the press. However, the location of the forging under the press is debatable; the way it is located under the press and the way it turns around its axis. Moreover, the proposed technique does not make it possible to make forgings of the conical shape.

Precision is one of the main requirements for the forging process. It significantly affects the margins at the finished forging, which impacts the consumption of metal. A special rocking device was developed to improve the precision of the rings [12]. The disadvantage of the proposed technique is that the forging after turning on the mandrel is not installed in the middle of the bottom striker but rolls onto it; there are also no parameters of distance from the vertical axis of the press, which give rise to eccentricity. This would be especially true for conical billets.

Paper [13] argues that in order to increase the metal utilization factor by reducing the size of the laps on a forging a bandage should be used to limit the outer diameter of the billet, as well as the width limiters of the billet. The bandage consists of two parts, the parting plane is located parallel to the end surfaces of the bandage. However, to implement this technique, one needs to use several bandages to expand the range of articles received. There are also no parameters of the billet used, the forging obtained, and the degree of deformation. In addition, the scheme of the connection involving a wedge is not quite clear. Moreover, the use of a bandage with a conical inner surface would lead to descend, so is not suitable for conical shells.

One of the problems with the rollout of hollow-like forgings is that this process is accompanied by the occurrence of a bend in the drift-pin (correction) under the influence of a deforming force. As a result of this bend, the drift-pin has a larger thickness of the wall inside than on the ends. As a result, there is an uneven redistribution of metal, which leads to the heterogeneity of plastic deformation and distortion of the shape of forging. To correct these shortcomings, work [14] proposed to use a drift-pin with a bandage mounted on it with a cylindrical work surface. The seating surface of the bandage is made with a curvilinear generatrix that corresponds to the line on the cylindrical axis, which is bent under the influence of a deforming force. The result ensures the uniform thickness of the forging wall for height and the uniform metal deformation. The proposed structure is complex and needs additional design elements, so a more practical solution to the issue of the drift-pine deflection is to replace it with a larger diameter.

Nuclear power plant reactors must meet safety and reliability characteristics. One of the main tasks for designers is to improve the operational characteristics and maintenance of the reactor units' bodies. To this end, engineers are developing new manufacturing processes of thermomechanical treatment. In addition, it is necessary to reduce the overall cost of production and prolong the life cycle of a reactor [15]. All this necessitates further research into the shape change of a billet and the resulting mechanical properties.

The structural elements of reactor bodies with a significant difference in cross-section size occupy a special place. These include conical shells, flanges, shells that are combined with flanges, both on the one side and on either side [16].

At present, most elements in the reactor unit with a variable cross-section are joined by welding individual elements, such as the shells and flanges. This complicates and prolongs the time of manufacture, reduces operational characteristics of the elements and, as a result, the structure in general. These operations can be eliminated by forging, which would be composed of several parts. Currently, in most cases, the complex conical profile of a part is covered with a lap. In further treatment, there are losses of metal, whose significant volumes are removed mechanically, whereby a significant amount of it is wasted. In addition to waste, the production time and the amount of energy resources that are used to machine the product are growing. As a result, there is an increase in the cost of making hollow forgings with a complex profile [17–20].

The industrial process of making conical hollow parts is very complicated. It includes steel smelting, casting it into ingots of the proper shapes, weight and size, their subsequent forging, thermal treatment, and machining. Up to now, a large enough number of materials have been designed, with many new materials under development, which are used to make parts for reactors [21, 22]. However, the manufacturing technologies of these materials, specifically forging that involves the use of sophisticated profiled tools, still need further study to be industrially implemented [23, 24]. These technologies are devised to reduce the cost of making a part and increase the competitiveness of an enterprise or company [25, 26]. One way to solve these tasks is to make the shape of a forging close to the shape of a specified part, thus reducing the amount of metal that is wasted and decreasing the utilization of cutting tools [27, 28].

A study of this specific area is reported in work [29]. By following the examined technique, it is proposed to obtain conical shells by rolling them out on the mandrel of step billets using a flat striker. However, the cited work considered obtaining only conical shells with a smooth outer surface. The considered technique does not identify the peculiarities of obtaining conical shells with a flange on the outer surface. Moreover, the step billets under the examined technique deform by a flat striker, which does not make it possible to receive the flange of a predefined height. In addition, the cited work established only the taper angle at rolling. For a more comprehensive assessment of a given process, the forging's relative diameters should be determined on the side of the protrusion and ledge. This information would make it possible for the technologist to devise a manufacturing process that could ensure that the assigned sizes of a forging are obtained. It should be noted that the taper formation is significantly affected by the degree of deformation (compression of the wall of a hollow billet). However, the above work did not establish these patterns. Therefore, techniques for obtaining conical shells with a flange require further studies to identify the features of shape change and the distribution of deformations in the process of rolling out by a step striker.

Given the above, this study aims to obtain hollow conically-shaped forgings with a varying thickness of the wall. It is proposed to obtain forgings by rolling them using a step striker. In the theoretical study, it is necessary to consider the stressed-strained state (SSS) of a forging and to determine the process parameters that are the most significant. Based on the results to be obtained, it is required to provide a procedure for devising the manufacturing process of forging, as well as the recommendations on the tool design and the extension of its scope of application.

3. The aim and objectives of the study

The aim of this study is to determine a shape change and the distribution of deformations in the process of deformation by a profiled tool in order to obtain conical shells with a flange, which would reduce allowances for machining and ensure that qualitative assessment of the machined structure of a billet is received.

To accomplish the aim, the following tasks have been set:

– to define a parameter for quantifying the taper formation of a conical hollow billet with a flange;

– to perform a finite-element simulation of the rolling of conical shells with a flange by a step striker and determine the gradual distribution of the intensity of logarithmic deformations in the process of rolling out conical shells;

– to establish the dependences of the shape change in a step billet for different relative diameters of the billet and rolling modes;

– to determine a change in the degree of compression in the protrusion and ledge of a billet in the process of deformation.

4. The study methods and materials

Each theoretical method is based on certain assumptions. Basically, these assumptions relate to the properties of the material (solidity, isotropy), friction conditions, temperature, the billet volume constancy, and do not take into consideration the inertial and mass forces. Most methods do not consider that strengthening that follows hot treatment and are built on the conditions of ideal plasticity or the rigid-plastic concept. The most accurate method should the method, which, while accounting for all assumptions and limitations, does not change the physical essence of the process. Given this, our theoretical study into the forging processes involving large forgings was based on a FEM that provides for a large amount of data on deformation processes, compared to similar research methods [30–34]. The method is widely used to solve problems of the plastic deformation of billets, SSS calculation, temperature field estimation in tasks that relate to metal forming [35–37].

FEM can be used to determine a change in the forging's diameters and establish the forging's expansion; these parameters in our study are important in the rolling process.

This work employed the software «Deform 3D» (USA) (temporarily licensed to the Donbas State Academy, Kramatorsk, Ukraine) for computations involving FEM. The numerical model of the deformation process is based on the flow theory. The material of a billet is considered to be an incompressible elastic-plastic body. The system of the initial equations [38] includes the following: an equilibrium equation ($\sigma_{ij,j}=0$), a motion equation $\left(\sigma_{ij,j}+\rho\dfrac{dv_i}{dt}=0\right)$, the kinematic ratios $\left(\dot{\varepsilon}_{ij}=\dfrac{1}{2}\left(v_{i,j}+v_{j,i}\right)\right)$, which determine the flow equations $\left(S_{ij}=\dfrac{2}{3}\dfrac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij}\right)$, etc.

Discretization of the above equations is based on the principle of virtual speeds and operations. The unknowns are the nodal values of speeds and mean stresses. The finite-element grid consisted of linear four-sided tetrahedra. The number of elements into which a billet was broken is 60,000 pieces.

The material of the billet is structural steel 34SrMo4 (selected from the software Deform 3D database). The heating temperature of the billet was 1,200 °C. The deformation rate was constant, 40 mm/s. The degree of deformation at each reduction of the press was 5 % from thickness wall of the hollow workpiece. The tilting angle of the billet is 20°. The billet was crimped at a constant deformation force along the entire length of the circle (run). The rolling process was implemented over 7 runs with a total deformation rate of 35 %. The Siebel friction factor between the billet and tool was 0.35. The deforming tool temperature is 40 °C.

5. Determining a parameter to assess the taper formation in a hollow billet

The quality of large forgings is determined by two general principles – the forging's geometric indicators, which include a taper, and indicators of the mechanical properties. These composite properties must meet the requirements by standards that regulate both the mechanical property levels and geometric dimensions. The latter are typically set by standards in the form of acceptable deviations in the size of the forging, as well as the allowance sizes. These allowances cover the inaccuracies of the size and curvature of the forging with a layer of additional metal. This metal would be removed during further machining. An increase in this metallic layer leads to the increased metal consumption in the manufacture of a part and, as a result, to the part's higher cost and the decreased metal utilization factor [39].

The basic technological parameter needed to develop the manufacturing process of rolling is a shape change during the deformation process. The billet's shape after rolling is determined by the taper of the inner hole, which was calculated from the following formula:

$$K=(d_p-d_l)/L_f,$$

where d_p is the internal diameter of a forging on the side of a protrusion; d_l is the internal diameter of a forging on the side of a ledge; L_f is the length of the forging.

In our theoretical study, the taper at rolling was defined as the difference in the coordinates (along the X axis). Four points were set on the edges of the hole in the billet's section in the ZY plane. Next, the coordinates were determined for these points in the rolling process. The maximum difference in the coordinates along the X axis over one full turn of the billet between the two opposite points was the examined diameter.

The result of the finite-element modeling has established the most significant sizes of a forging for the analysis of a shape change. The basic initial parameters for the process of step billet deformation are the diameter of the billet's protrusion D_p/d_{av}, the diameter of the billet's ledge D_l/d_{av}, and the deformation degree ε.

6. Gradual distribution of the intensity of logarithmic deformations in the process of rolling conical shells

Taper forms at the simultaneous crimping of the protrusion and ledge as a result of the larger degree of deformation on the side of the ledge. In order to form a taper on the side of the protrusion, it is necessary to create such conditions owing to which the protrusion would receive a greater degree of deformation. To this end, before rolling, a billet should have a ledge height greater than the height of the step on the deforming tool (Fig. 1). As a result, there is a gap at the beginning of the rolling between the striker and a billet's ledge. This would cause the protrusion to deform at the beginning of the deformation process, and only then the protrusion and ledge would be crimped at the same time. As a result, during the first full turn of the billet at rolling, the ledge would not be crimped.

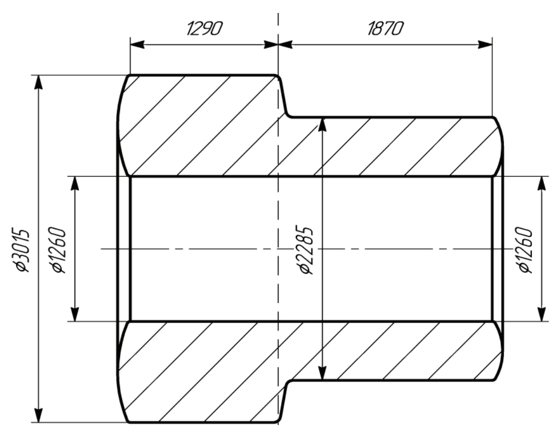
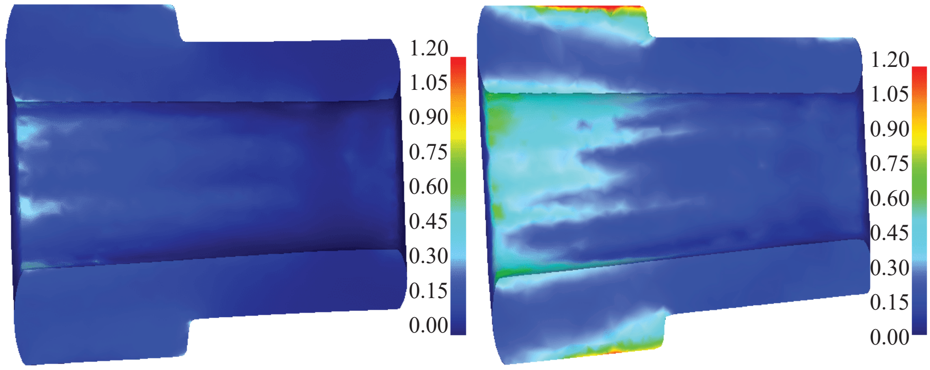


Fig. 1. The shape and size of the original step billet

The result of the finite-element modeling has established that over the first full turn of rolling only the protrusion deforms; a forging is formed with a taper on the side of the protrusion. However, the hole has a cylindrical section (Fig. 2, *a*) whose length is approximately 500 mm. Its occurrence is due to that only that part of the billet deforms when pressed that is located under the protrusion. At the second full turn of crimping (Fig. 2, *b*), the deformation of the ledge begins and this cylindrical section disappears. At the same time, the lengthening on the side of the forging's ledge is more intense than that on the side of the ledge. Based on the modeling results, it was established that following the second round of rolling the deformations in the protrusion exceed those in the ledge. Moreover, the maximum logarithmic deformations are concentrated on the outer surface of the forging on the side of the protrusion.



a *b*

Fig. 2. A shape change and the distribution of logarithmic deformations: *a* – after the first run in a circle; *b* – after the second run in a circle

The decrease in the diameter on the side of the ledge led to that a lower degree of deformation is concentrated in it due to that it begins to deform later. At the same time, there is a taper of the forging's hole.

7. The dependences of shape change in the step billet for different relative diameters of the billet and rolling modes

The resulting billet after forging (Fig. 3) demonstrates a taper, which is 1:13 (0.078). At the same time, the billet has a reverse taper with an increased diameter on the side of the protrusion. Moreover, the maximum logarithmic deformations are localized at the surface of contact between a striker and a billet. That was contributed to by an increase in the ledge height on the billet relative to the step at the deforming striker.

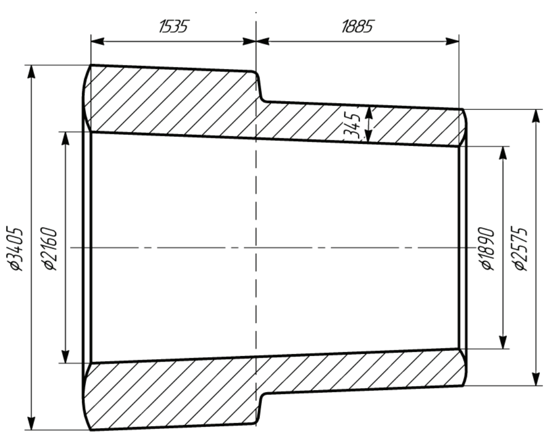


Fig. 3. Drawing of the billet after deformation

Our analysis of the results of shape change at deformation (Fig. 4) has made it possible to determine that the taper increases over the first full run of crimping. This is due to that only one side of the billet is rolled out. When a deforming tool begins to crimp the ledge, the taper decreases. This can be explained by the onset of the intensive deformation of the billet on the side of the ledge due to the that a low ledge undergoes a larger relative deformation. However, the taper does not completely disappear.

Our analysis of results of changing the internal diameters of the ledge and protrusion depending on the degree of crimping a ledge has revealed the following. At a protrusion crimping degree of ε_p<0.1, the internal diameter on the side of the ledge d_p increases while the internal diameter on the side of the ledge d_l does not change. This is due to that over the first full turn of crimping a billet the ledge does not undergo deformation. During the subsequent crimping, there begins a gradual increase in d_l, which is associated with the onset of crimping the ledge; in this case, the increase in the diameters on the side of the ledge (d_l) and protrusion (d_p) proceeds in parallel (Fig. 5).

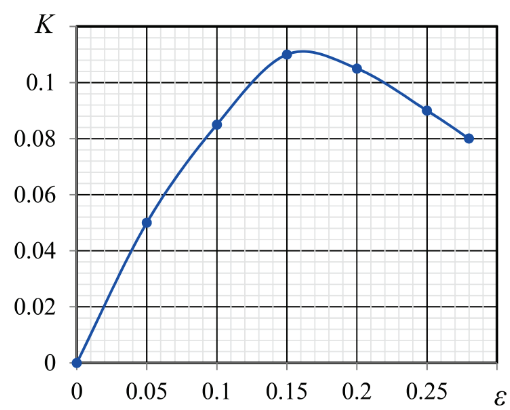


Fig. 4. Change in a forging's taper (*K*) depending on the degree of crimping on the side of the ledge ε

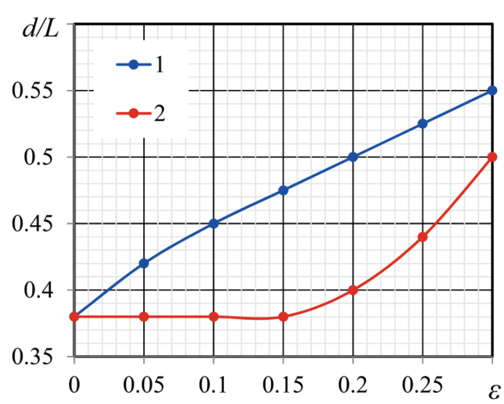


Fig. 5. Change in a forging's diameters *d*/*L*: 1 – protrusion, 2 – ledge, for varying degrees of crimping the protrusion

This can be explained by that the difference between the total crimping of the ledge and protrusion decreases. At the end of the rolling, the increase in d_l is more intense than that in d_p; the distance between the curves decreased (Fig. 5). This is due to that over the last full turn of a billet at crimping the increase in the degree of the protrusion deformation was less than that in the ledge.

8. Change of a crimping value in the protrusion and ledge of a billet in the process of deformation

Our analysis of the results on the degree of crimping a billet's sections at rolling has made it possible to establish that during the deformation process the deformation in the ledge accumulates (Fig. 6). The increase in the degree of crimping a ledge is due to the occurrence of intense stretching tangential deformations. Thus, when the ledge is crimped, the ledge has already acquired a certain degree of deformation.

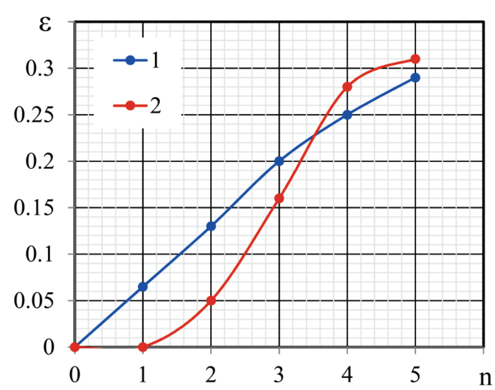


Fig. 6. Change in the relative crimping degree ε for different number of runs: 1 — protrusion, 2 — ledge

Thus, we can conclude that in order to reach the maximum taper value, it is necessary to reduce the degree of crimping a ledge. In other words, it is necessary to increase the height of the ledge relative to the height of the step at a deforming tool. This would cause the ledge to deform later and, as a result, would not help reduce the taper. That could make it possible to obtain hollow shells with a greater taper.

9. Discussion of results of studying the process of rolling conical shells with a flange

The results of modeling the process of rolling conical shells with a flange have established patterns of taper formation when forging step billets. Our findings can be explained by that when the step shells are rolled out, the taper on a hollow billet is formed as a result of the following processes. At first, only the protrusion is crimped (the ledge is not deformed). As a result, the outer and inner diameters on the side of the ledge (Fig. 5) are increased. This ensures that the forging acquires a conical shape (Fig. 3). The taper in the process of such rolling increases until the moment when the ledge begins to deform (Fig. 4). Next, the taper begins to decrease due to that the internal and outer diameters on the side of the ledge begin to increase intensively (Fig. 5, curve 2). The results obtained are further supported by that during rolling there is an accumulation of varying degrees of deformation in the protrusion and ledge (Fig. 6). Crimping the l protrusion and ledge by the same value leads to that the internal and outer diameters on the side of the ledge increase more intensively.

A special feature of the proposed method is that the sequential rolling of the protrusion and ledge produces a conical shell with a flange, which was not possible to obtain by applying other techniques [8, 11, 12].

In comparison with a known study in a given area [29] (rolling step billets with a flat striker to produce smooth conical shells), our work has established patterns in the shape change and distribution of deformations when rolling step billets with a step striker. This has improved the technological capabilities of the rolling operation to obtain conical shells with a flange. We have established the quantitative patterns of taper formation in hollow shells while maintaining the specified height of the flange, as well as a comprehensive indicator for the rolling process – the relative diameters of a forging on the side of the protrusion and ledge. The resulting patterns would make it possible for a technologist to devise a manufacturing process that could warrant obtaining the specified sizes of a forging.

This work has also tackled the effect of a degree of crimping (deforming) the wall of a hollow billet on the formation of taper and relative diameters of the forging. The advantages of the new technique for forging conical rings compared to the conventional technique:

– by using the proposed technique, it has become possible to obtain conical shells with a flange. This has allowed a decrease in the lap size whereby the consumption of metal decreased by 10...15 %;

– the rolling of conical shells has made it possible to fabricate forgings that repeat the shape of conical parts, which resulted in a shorter time for machining.

However, there are certain limitations to this study:

– the reported results are only suitable to roll conical shells with a flange;

– the crimping degrees of the walls of a hollow billet are limited to the level of up to 30 %;

– the process of rolling a step billet with a more universal flat striker has not been considered.

There are some drawbacks in studying the new manufacturing process of forging:

– the different deformation degree of the protrusion and ledge of a step billet may lead to different mechanical properties in these zones;

– the taper formation of a forging complicates the process of edging the hollow billet on a mandrel and results in the increased labor-intensity of forging;

– the process of increasing the internal and outer diameters on the side of the ledge has not been considered.

It should be noted that this paper has not investigated the processes of obtaining such conical shells by rolling that have an extension on the side of the ledge. Given this, further modeling of the processes of forging step shells should address the identification of patterns that would make it possible to establish the influence of the shape and size of a step billet on an increase in the diameters on the side of the ledge.

10. Conclusions

1. A relative parameter has been proposed to quantify the taper formation in a forging during the operation of rolling a step billet.

2. Based on the simulation results, we have established a gradual distribution of the intensity of logarithmic deformities in a billet's body in the process of rolling conical shells. It was found that the stepped deformation leads to an increase in the uneven distribution of deformations on the side of the protrusion and ledge. Maximum logarithmic deformations of 1.0...1.2 occur at the inner and outer surfaces of a step billet's protrusion.

3. The dependences of shape change in the step billet for different ratios of geometric sizes and rolling modes have been established. It was found that the maximum taper for a predefined ledge height would be obtained at a deformation degree of 15 %.

4. It has been established that the amount of crimping in the protrusion and ledge is leveled after 3 full turns (runs) of the billet when forging a step billet.

Acknowledgments

The study and our paper were financed within the state-funded research by the Ministry of Science and Education of Ukraine (State registration No. 0120U101973) «Development and research of a new technological process for the manufacture of whole forged step shells for reactor blocks at nuclear power plants».

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