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MODELING THE TECHOLOGICAL PROCESS OF PIPE FORGING WITHOUT A MANDREL

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Досліджено спосіб протягування товстостінних труб. Запропонований спосіб полягає в деформуванні пустотілої заготовки без оправки. Розроблено методику проведення теоретичних досліджень МСЕ. Методика призначена для визначення теплового, деформованого стану та формозміни заготовки при куванні труб без використання оправки. Змінними параметрами були внутрішній діаметр пустотілої заготовки, який варіювався в інтервалі 0.30; 0.55; 0.80. На основі скінчено-елементного моделювання були встановлені: розподіл температур і інтенсивності логарифмічних деформацій в об’ємі труби після протягування без використання оправки. Визначався діаметр отвору труби, який утворюється при протягуванні даним способом. Встановлювалися залежності інтенсивності подовження та потовщення стінки труби. Був розроблений спеціальний показник для оцінювання подовження труби. Було визначено, що при збільшені внутрішнього діаметру подовження труби збільшується та знижується інтенсивність зменшення отвору. Загальною залежністю змодельованих схем протягування є те, що величина подовження пустотілої заготовки несуттєво змінюється для різних ступенів обтискань при сталих відносних розмірах труби. Це дозволило встановити рекомендовану подачу для збільшення подовження пустотілої поковки та зменшення ступеня закриття отвору. Раціональна подача повинна складати (0.05...0.15)D. Результати скінчено-елементного моделювання перевірялися експериментальними дослідженнями на свинцевих зразках. Була запропонована методика експериментального моделювання. Встановлено, що при внутрішньому діаметрі заготовки (0.5...0.6)D, спостерігається максимум потовщення стінки. Встановлено, що результати з формозмінення заготовки, які отримані у теоретичному дослідженні МСЕ, на 9...14 % більше за експериментальні. Достовірність результатів теоретичного моделювання підтверджується даними експерименту зі зменшення внутрішнього діаметру труби. Різниця теоретичних результатів й експериментальних складає 9...12 %. Встановлені закономірності дають можливість визначати остаточний діаметр отвору труби. За результатами моделювання встановлено, що протягування трубних заготовок без оправки цілком можливе. Цей спосіб розширює можливості техпроцесів виготовлення трубних заготовок

Ключові слова: товстостінна труба, протягування без оправки, кування, заковування отвору, подовження заготовки, МСЕ, тепловий стан, деформований стан

1. Introduction

A priority task for the development of power engineering is to reduce the cost of parts and to improve their mechanical properties [1–3]. Such parts include thick-walled pipes. These forgings must be produced by forging on a mandrel. However, the thick-walled pipes are manufactured from solid shafts by using the operation of drilling a hole [4]. The result is the increased time of machining, enhanced consumption of metal, as well as fiber cutting. This relates to the fact that, given the pipe length exceeding 4,000 mm and a diameter of the hole less than 300 mm, using a mandrel during broaching is impossible [5]. Therefore, the issue on making the workpieces for thick-walled pipes remains relevant, thereby requiring a comprehensive analysis and improvement [6].

2. Literature review and problem statement

Based on an energy method, paper [7] devised a model for installing an axial drawing for a workpiece when deforming pipe workpieces at radial-forging machines. The authors determined the influence of reduction and feed of a hollow workpiece on the strength and change in the profile in a meridional cross-section of the pipe. However, the established model does not make it possible to determine the lateral deformation of a metal at forging, which requires that problem should be solved in a 3D setting.

Article [8] proposed a technological process of pipe forging, during which the resulting workpiece is heated and post-pressed. Additional die equipment provides for the conditions under which a metal of the workpiece flows in the central part.

Study [9] applied a finite-element analysis to examine the technological process of pipe forging without the use of a blacksmith mandrel. Based on modeling results, it was found that the devised technological process could be used at a small feed of a workpiece to the tool. Forging without the use of a blacksmith mandrel at significant axial feeds increases the level of axial force, which may lead to the formation of gaps.

The results from work [10] established a three-dimensional model of the technological process of pipe broaching using a mandrel by applying a finite element method (FEM), and analyzed the strained state of a hollow workpiece at broaching. The authors proved the feasibility of a reduction technique for four sides of a pipe workpiece with an inner mandrel. It was determined that the turning angle of a hollow workpiece has no decisive influence on changing the shape of an article. It was established that broaching pipes with a small hole using a mandrel is not possible, due to a warp in a thin mandrel and the complexity of pulling it out of the forging.

Paper [11] experimentally investigated techniques of radial forging of pipe workpieces. The examined technique implied the improvement of equipment for the possibility of broaching not at hammers, but at hydraulic pressing units. The paper has established a pattern in the change of a pipe workpiece's wall at broaching.

Study [12] reported results on pipe broaching without the use of a blacksmith mandrel. It was established that the absence of a mandrel helps reduce the hole and weakly lengthens the pipe. Experimental data on broaching techniques without using a mandrel have made it possible to determine that the created different thickness along the wall of the pipe was about 2 %. However, the study misses information on the impact of shape and size of forging dies on the lengthening of a pipe at forging without a mandrel.

Paper [13] established the impact of the geometry of a deforming tool on the stressed-strained state in the process of pipe forging on a mandrel. It was established that for manufacturing a hollow forging with the maximal uniformity in the distribution of intensities of deformations and mechanical characteristics along the wall of a pipe it is advisable to use a deforming tool with a convex surface. The results from experimental simulation of a pipe forging technique at radial-forging machines helped find that the examines process makes it possible to improve the strength and viscosity of a metal [14]. The author established a dependence for determining the axial, radial, and circumferential deformation of a workpiece. He defined the influence of reduction on the technological modes of broaching using a mandrel. However, papers [13, 14] failed to establish the impact of a deformation technique on the formation of texture, which increases the anisotropy of the mechanical characteristics for a material.

Study [15] modelled the techniques for radial forging of pipe workpieces using a mandrel. The results from experimental simulation were used to manufacture pipes of different diameters and walls. The authors carried out the deformation by using four peens, which contributed to guiding the flow of a metal of the workpiece along the axis, thereby reducing the extension in the process of forging.

The process of forging pipe workpieces was used to investigate the influence of a peen shape on determining the forging of axial part of an ingot [16]. The research found that it is possible to obtain uniform mechanical characteristics in the transverse and longitudinal directions by improving the shape of peens.

The increase in the accuracy of size of the outer and inner parts of metal pipes after forging using a mandrel is reported in [17]. The authors found that increasing the angle of cutting peens improves the uniformity of deformation distribution. Increasing the reduction contributes to improving the accuracy of a pipe's hole, but such an increase may lead to crack formation.

Paper [18] studied the impact of segregation distribution in a workpiece at forging, which made it possible to refine the modes of heat treatment. The authors developed a program in order to study the process of pipe deformation.

Studies [19, 20] compare the processes of pipe forging with three and two peens without the use of a mandrel. The research results established that the process of broaching with two forging peens leads to a more intensive formation of defects at the surface than when broaching by using three peens [21–23]. It was found that the forging effort when using two peens is larger than that when three peens are applied. Deformations inside the body of workpieces when forging pipes with three peens are distributed evenly. However, such a pipe forging technique cannot be used for the manufacture of long pipes.

An analysis of the scientific literature has revealed that the issue on manufacturing the thick-walled pipes has not been solved up to now. The most advanced methods are the broaching techniques without using a mandrel. However, neither SSS nor a shape change in a pipe's hole in the broaching process without using a mandrel have not been established. Thus, there is a need to improve and explore the processes of pipe broaching without the use of a mandrel. Devising new technological processes for pipe forging without the use of a blacksmith mandrel requires comprehensive modeling and preparation of recommendations for their implementation.

3. The aim and objectives of the study

The aim of this study is to devise a process of forging thick-walled pipes without the use of a blacksmith mandrel in order to reduce the time and consumption of a metal while machining pipes of responsible designation.

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

– to devise a methodology for theoretical and experimental research into the processes of pipe forging without a mandrel;

– to establish the thermal, strained state, and to determine the impact of the inner diameter of a pipe workpiece on a change in the length of the pipe at forging without a mandrel, and to identify patterns of change in the relative thickness of the wall of a pipe workpiece during forging without the use of a mandrel;

– to test data from the finite-element modeling of change in the shape of a workpiece at broaching without the use of a mandrel by conducting laboratory experiments.

4. Procedure for modelling the processes of broaching pipe forgings without the use of a blacksmith mandrel

4. 1. Theoretical modelling of shape change, thermal state, and the distribution of strains

We simulated changes in shape, the thermal state of a workpiece, as well as the deformed at forging without the use of a mandrel, based on FEM employing the software suite Deform 3D. The material chosen was steel of grade 40X, the temperature range when treating by pressure was 1,180...790 °C. Poisson's ratio was 0.3, the Young modulus of elasticity of first kind was $2 \cdot 10^5$ MPa. The temperature of heating a workpiece $t=1{,}180$ °C, the motion velocity of the deforming tool $v=30$ mm/s; the pipe diameter $D=1.0$ m. The inner diameter in relative ratio (d_0/D) was 0.30, 0.55, 0.80. Schematic of the deformation process is shown in Fig. 1.

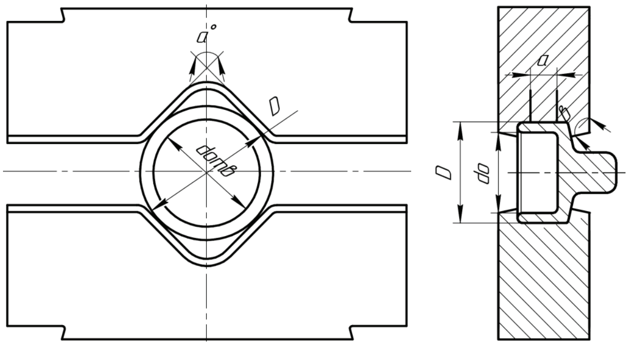


Fig. 1. Estimated scheme of forging without the use of a blacksmith mandrel: *a* – front view; *b* – side view

The length of hollow ingots varied in the range of 288, 330, and 480 mm. To handle and maintain a workpiece at deforming, we used a technological pin, which required the use of pipe workpieces with bottom (Fig. 1).

4. 2. Procedure of experimental modeling

We experimentally studied the process of pipe forging using lead samples. The lead was introduced with 1.0 % of antimony, which brought the rheological properties of the material closer to steel of grade 40X with a temperature of hot treatment by pressure. The outer diameter of the workpieces was 50 mm, height – 24 mm, the inner diameter of a hollow workpiece varied in a range of 12.25; 22.5; 35 mm; the feed was 10 % of the diameter (D); a scaling factor was 1:20. Hollow lead samples were produced by casting into a mold. Parallelism of the deforming tool was ensured by a stamp package (Fig. 2). Deformation was carried to the outer diameter of 26 mm. In the process of experimental studies, we measured the dimensions of a pipe's hole.

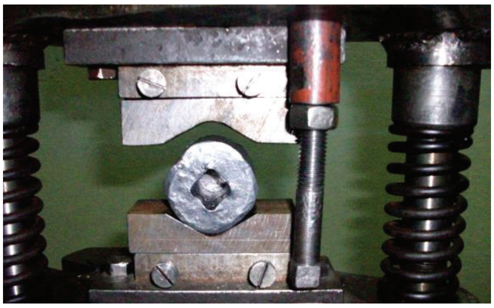


Fig. 2. Equipment for experimental modeling

Forging was conducted at hydraulic pressing unit of power 0.5 MN. The speed of the tool was 1.5 mm/s, which would correspond to the kinematic conditions of similarity. When deforming, we measured dimensions of the models and the forging effort at broaching with a reduction of 5 %. We measured the volume of the cavity in a forging piece using a dimensional volumeter. The depth and volume of the cavity defined the diameter of a pipe's hole after broaching without the use of a blacksmith mandrel.

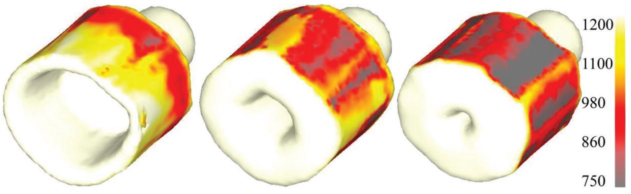
5. Results of theoretical modelling the thermal, strained state, and a shape change in a workpiece at broaching without a mandrel

We have improved the technological process of pipe deformation without the use of a blacksmith mandrel, which implied performing operations of perforation and broaching. The final broaching of workpieces was carried out without the use of a mandrel. At present, this method is not studied sufficiently; in addition, there are no recommendations for implementing a given forging technique.

Changing the shape of pipe workpieces during forging without using a blacksmith mandrel depends on strained state (SS). SS depends on a shape and size of the deforming tool and deformation parameters. The process of pipe broaching without the use of a mandrel is accompanied by an increase in the pipe wall. Therefore, to determine the patterns in changing the internal diameter of a pipe workpiece, one should explore the impact of pipe broaching when using peens with cuts.

In order to accurately determine SS, one should find the distribution of a forging's temperatures at forging. Temperature distribution after deformation would make it possible to determine the required number of heating cycles. The distribution of temperatures within a workpiece was determined by using FEM.

An analysis of temperature distribution data inside the body of a workpiece after deformation, 20 %, revealed that the temperature drop in terms of volume corresponds to a temperature range of deformation of steel of grade 40X for the examined size of the pipe (Fig. 3). The average temperature drop within the volume of the forging is 350 °C. As a result, the number of heating cycles, in comparison with a standard technology, decreased from two to a single heating cycle. The results obtained can be explained by the fact that deformation without the use of a mandrel is not accompanied by the dissipation of thermal energy towards a cooling mandrel, as is the case for a standard forging technique. The result is the extended technical capabilities for the deformation of pipe workpieces because of the increased number of pressings over a single heating cycle.

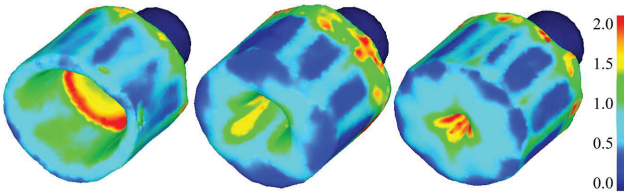


a *b* *c*

Fig. 3. Distribution of temperatures after forging without the use of a blacksmith mandrel for different inner diameters (d_0/D): *a* – 0.80; *b* – 0.55; *c* – 0.30

Deformation changes the cross section of a workpiece. When the cross section of a workpiece enlarges prior to deformation and at the same degree of reduction, the length of the workpiece after the deformation would increase (according to the law of constancy of volume).

We investigated of the process of pipe deformation without the use of a mandrel by peens cut at 115° and a feed of 50 % of the original diameter of the workpiece (Fig. 4). An analysis of the results obtained has made it possible to establish that deformation without the use of a mandrel reduces the hole of a pipe (Fig. 5). The decrease in the inner diameter is made up by the enlarged wall and a decrease in the outer diameter.



a *b* *c*

Fig. 4. The strained state after deformation without using a mandrel for workpieces with an internal diameter (d_0/D) of: *a* – 0.80; *b* – 0.55; *c* – 0.30

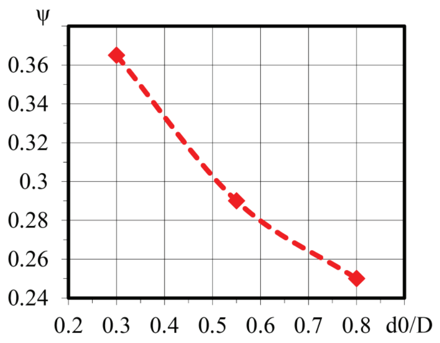


Fig. 5. Dependence of workpiece elongation on relative inner diameter when reducing a pipe by 20 %

When reducing a workpiece with equal outer diameters for the same deformation, a decrease in the inner diameter is defined by the thickening of a pipe's wall. When broaching without the use of a blacksmith mandrel, we have determined the impact of the inner diameter of a workpiece (d_0/D) on its elongation (Fig. 5). It was found that increasing the inner diameter of a workpiece increases the forging inner diameter. At the same time, the elongation of a workpiece (ψ) reduces.

Changing an inner diameter for different sizes of a workpiece should be carried out based on the parameter that accounts for elongation. This parameter is defined by the ratio of difference in the areas of a workpiece prior to deformation and forging to the reduced area:

$$f=\frac{F_0-F_k}{F_{red}}=\frac{(D^2-d^2)-(D_k^2-d_1^2)}{D^2-D_k^2},$$

where F_0, F_k is the original and resulting cross-sectional area of a workpiece; F_{red} is the cross-sectional area of the reduced workpiece; D, d_0 are the outer and inner diameters of the original workpiece; D_k, d_1 are the outer and inner diameters of a forging.

The proposed indicator makes it possible to determine the elongation of a hollow workpiece at different deformations of a pipe workpiece. In other words, this parameter shows part of the area of a reduced pipe workpiece, which leads to the lengthening of the pipe. At $f\to 0$, a pipe does not elongate. At $f\to 1$ ($F_0-F_k=F_{red}$), the entire change in area is aimed at increasing the lengthening of the pipe.

Forging pipes with conventional peens does not lead to an observable lengthening of the pipe. Increasing the inner diameter of a pipe leads to a decrease in length. This can be explained by the following – at large inner diameters (thin walls), a metal would flow in the direction of thickening of the wall of the forging rather than towards increasing its length. Consequently, one should improve the technique of pipe broaching without the use of a blacksmith mandrel in order to increase the length of a forging.

6. Results of experimental modeling of shape change in a hollow forging when forging without using a mandrel

Lead models were deformed by peens cut at 115° and a feed of 10 %. These parameters were set based on the results from modelling using FEM as the rational ones for intensive elongation at forging. Broaching was executed in runs with a deformation of 5 % at each stage. The deformation was performed in the following sequence: a run lengthwise → rotation of a workpiece at 90° → a run lengthwise → rotation of a workpiece at 90° → a run lengthwise → rotation of a workpiece at 90° → a run lengthwise → rotation of a workpiece at 45° → a run lengthwise. Such a deformation sequence ensures that a workpiece is shaped in the form of a polyhedron, which is close to cylinder. Under the preset modes of deformation, the process of deformation does not lead to the formation of folds at the surface; the maximum flow of a metal is achieved along the axis of a forging.

Results from a theoretical study were compared with experimental data. Fig. 6 shows data on experimental simulation when deforming workpieces of inner diameters (d_0/D) of 0.80, 0.30, 0.55 by cut peens. We have built graphic dependences for pipe lengthening (f) (Fig. 7), thickening of its wall (Fig. 8), and a change in the inner diameter of a pipe (d_{1cp}/D) (Fig. 9).

It was determined that increasing the inner diameter lengthens the pipe and reduces closing a hole (Fig. 7). The established results can be explained by a thin wall that provides for a small amount of metal, so the less amount of the metal flows in the direction of wall thickening.

a *b* *c*

Fig. 6. Experimental hollow workpieces with different inner diameter (d_0/D) after deformation by 20 %: *a* – 0.80; *b* – 0.55; *c* – 0.30

The data on pipe workpiece elongation, acquired from theoretical modelling, exceed the data from the experiment by 8...14 % (Fig. 7). In addition, the thickness of a wall is growing more intensively for lead samples (Fig. 8).

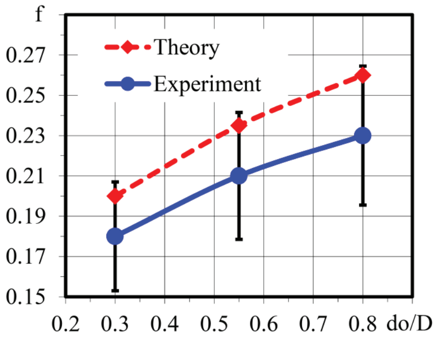


Fig. 7. Dependence of pipe workpiece lengthening on the inner diameter of a workpiece

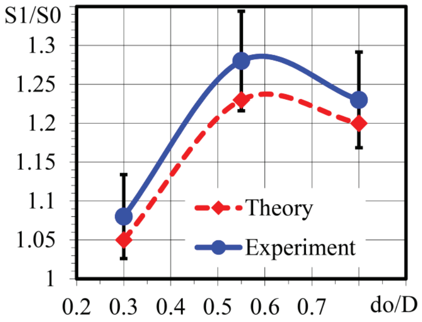


Fig. 8. Change in the thickness of a pipe wall depending on the inner diameter of original workpiece

Experimental study has made it possible to determine (Fig. 8) that increasing the inner diameter of a pipe workpiece to 0.6 leads to the extreme thickening of its wall. The inner diameter exceeding 0.6 leads to a decrease in the thickness of the wall.

FEM data and experimental data have made it possible to determine the extreme thickening of a wall, which occurs at a relative diameter of 0.55...0.60 (Fig. 8). It was established that such ratios for a pipe workpiece are ineffective at broaching without the use of a mandrel due to the intense thickening of the pipe wall. Discrepancy between experimental data and those obtained theoretically is 5...7 %.

The accuracy of modeling results, when using FEM, about the decrease in inner diameter depending on the inner diameter of a workpiece (Fig. 9), is confirmed experimentally. Difference between experimental and theoretical results is 9...12 %.

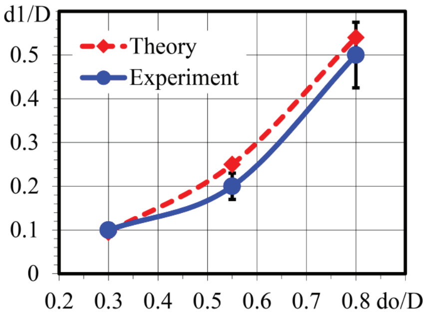


Fig. 9. Dependence of the decrease in inner diameter on the inner diameter of a workpiece at deformation without using a mandrel

The detected patterns are similar. The regularities established make it possible to determine the inner forging diameter of a pipe. Increasing the inner diameter of an original workpiece leads to an increase in the inner diameter of the forging.

7. Discussion of results of manufacturing the forgings of pipes without the use of a mandrel

We have devised a new technique to broach pipes without the use of a mandrel. We have established the distribution of temperatures, deformations, as well as dependences of change in the inner diameter and the thickening of the wall of a pipe workpiece at broaching without the use of a mandrel. The obtained results have made it possible to define the rational geometric parameters for a pipe workpiece to be deformed without a mandrel, as well as the advantages over existing broaching techniques for hollow articles:

– we have improved a technique to manufacture thick-walled pipes with an inner diameter less than 300 mm (super-high pressure pipes, strings for drilling rigs, etc.). Previously, such articles were made from solid billets by drilling. That required considerable time cost for machining and increased the consumption of metal;

– deformation of pipes without the use of a mandrel has made it possible to reduce the number of heating cycles for workpieces by excluding the cooling that is inherent to the broaching technique on a cooling mandrel, mounted inside the hole of a pipe workpiece. The result is the reduced time of deformation and lower energy costs to heat the workpiece;

– the devised forging technique without the use of a blacksmith mandrel makes it possible not to use specialized mandrels made from heat resistant steel;

– the deformation without the use of a mandrel changes the distribution of temperatures and deformations of a pipe workpiece. As a result, at reduction, a metal flows not only in the longitudinal direction, but also across the axis of a forging;

– a parameter has been constructed for elongating a workpiece, which defines the rate of elongation of a pipe workpiece over the speed of wall thickening, which makes it possible to estimate a shape change in the workpiece at broaching without the use of a mandrel.

One should note the following limitations in the devised technique for the deformation of thick-walled pipes:

– deformation without using a mandrel leads to the flow of a metal across the axis of a pipe that results in the wall elongation and complicates handling a shape change of the workpiece. That requires that the specified modes of deformation should be strictly followed;

– the absence of an inner mandrel necessitates an increase in the margin for the inner diameter of a pipe;

– the proposed broaching technique should be used only for the manufacture of thick-walled pipes.

Recommendations on the geometric parameters for workpieces, compiled in the current work, are of significant scientific and practical value; they could be used in the theory and technology of deformation processes of hollow articles without using a mandrel.

The practical aspect of applying the results of modeling is the improved technological process of pipe broaching whose inner diameter <300 mm, when the application of a mandrel is impossible.

Previously, scientists investigated the processes of deformation of pipe workpieces that employed mandrels. Broaching without the use of mandrels is a complex process; it, however, extends the technical capabilities of pipe deformation.

This work does not report results related to the possibilities of the devised process to make pipe workpieces by peens of a special shape, which could increase the intensity of a metal flow in the axial direction to enable the manufacture of thick-walled pipes. Therefore, there have remained the unresolved issues on determining the influence of shape and size of a workpiece and the shape of a deforming tool on increasing the elongation of a pipe workpiece at deformation without the use of a mandrel.

8. Conclusions

1. It was determined that the temperature drop within the volume of a forging does not exceed the limits of hot treatment by pressure. The average difference in temperature within the volume of a forging is 350 °C. The result is that the number of heating cycles at final broaching decreased from 2 to 1 cycle in comparison with the standard forging technology.

2. It was established that increasing the inner diameter of a workpiece leads to that the elongation increases while the forging of a hole decreases. The general dependence within the simulated processes of deformation implies that lengthening takes place insignificantly at different levels of deformation for the fixed size of a pipe workpiece. That has made it possible to establish the recommended feed and reduce the forging of an inner diameter. The rational relative feed for an intensive broaching of a hollow piece is 5...15 % of the workpiece diameter. A relative inner diameter of 0.55...0.60 results in the maximum thickening of a forging wall.

3. Results of elongating a workpiece, acquired by using FEM modeling, exceed those obtained experimentally by 9...14 %. Thickening of the wall occurs faster during the experiment. The accuracy of results from theoretical modelling is confirmed by the experiment to reduce an inner diameter depending on the inner hole of an original workpiece. Difference between the data from theoretical modeling and experimental study in this case is 6...12 %. The detected patterns are similar. The regularities established make it possible to determine the resulting diameter of a pipe's hole.

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