15. Bondarenko O. S. Systema otsinky efektyvnosti upravlinnia finansamy pidpryiemstva u suchasnykh umovakh // Investytsiy: praktyka ta dosvid. 2016. Issue 16. P. 18–21.
16. Ayvazyan S. A. Prikladnaya statistika: Osnovy modelirovaniya i pervichnaya obrabotka dannyh. Moscow: Finansy i statistika, 1983. 471 p.
17. Gribovskiy S. V. O povyshenii dostovernosti ocenki rynochnoy stoimosti metodom sravnitel'nogo analiza // Voprosy ocenki. 2002. Issue 1. P. 2–10.
18. Plyuta V. Sravnitel'niy mnogomerniy analiz v ekonomicheskih issledovaniyah. Metody taksonomii i faktornogo analiza / V. M. Zhukovskaya (Ed.). Moscow: Statistika, 1980. 151 p.
19. Vydannia ofitsiyne. Statystychnyi kontrol (kontrolni karty Shukharta) // Derzhstandart Ukrainy No. 69 vid 01 liutoho 2002 r. Kyiv, 2002. 32 p.

UDC 621.735.3-416
DOI: 10.15587/1729-4061.2018.142674

IMPROVING THE QUALITY OF FORGINGS BASED ON UPSETTING THE WORKPIECES WITH CONCAVE FACETS

O. Markov
Doctor of Technical Sciences, Professor,
Head of Department*
E-mail: oleg.markov.omd@gmail.com
V. Zlygoriev
PhD
Private Joint Stock Company
«Novokramatorsky Mashinostroitelny Zavod»
Ordzhonikidze str., 5, Kramatorsk,
Ukraine, 84305
E-mail: zvn@nkmz.donetsk.ua
O. Gerasimenko
PhD*
E-mail: profalliance@i.ua
N. Hrudkina
PhD**
E-mail: vm.grudkina@ukr.net
S. Shevtsov
PhD**
E-mail: sheser.ssa1@gmail.com
*Department of Metal Forming***
Department of Higher Mathematics*
***Donbass State Engineering Academy
Akademicheskaya str., 72, Kramatorsk,
Ukraine, 84313

Запропоновано спосіб кування поковок, який полягає в осаджені заготовок з увігнутими гранями. Розроблено методику теоретичних досліджень, яка полягала в дослідженні механізму закриття штучних осьових дефектів в заготовках. Дослідження проводилися на основі методу скінчених елементів. Основним параметром дослідження була глибина увігнутих граней заготовки. Цей параметр варіювався в діапазоні 0,75; 0,80 і 0,85. Кут увігнутих граней становив 120°. Результатами теоретичних досліджень були розподіли: деформацій, температур і напружень в тілі заготовки в процесі осадження заготовок з увігнутими гранями. На основі цих параметрів встановлювався показник напруженого стану в осьовій зоні заготовки.

Для перевірки отриманих теоретичних результатів була розроблена методика експериментальних досліджень. Дослідження проводилися на свинцевих і сталевих заготовках. В результаті теоретичних досліджень було встановлено, що ефективною глибиною увігнутих граней є співвідношення діаметрів виступів і уступів рівних 0,85. Для цього співвідношення відбувається інтенсивне закриття осьового дефекту. Це пояснюється високим рівнем стискають напружень при осаджені заготовок з увігнутими гранями. Встановлена ефективна ступінь деформації, при якій відбувається інтенсивне закриття дефектів. Встановлені розподіл деформацій за перерізом і висоті заготовки, а також зміна показника напруженого стану в процесі осадження заготовок з увігнутими гранями. Закриття осьових дефектів було підтверджено експериментальними дослідженнями на свинцевих і сталевих зразках.

Було здійснено впровадження нового способу осадження заготовок з увігнутими гранями. Результати ультразвукового контролю дозволили встановити, що отримані деталі не мають внутрішніх дефектів, які перевищують вимоги європейського стандарту SEP 1921. Проведені дослідження дозволили зробити висновок про високу ефективність запропонованого нового способу осадження заготовок з увігнутими гранями, яка полягала у підвищенні якості осьової зони крупних поковок з використанням цього способу

Ключові слова: увігнуті грані, осадження, напружено-деформований стан, осьові дефекти злитка, високоякісні поковки

1. Introduction

All machine parts in heavy industry and energy engineering refer to the products that have special purposes and are manufactured using the techniques of hot plastic deformation. The dimensions and weight of these parts imply their fabrication by forging. Billets for forging are typically ingots. Forge ingots are characterized by low quality due to the existence of cast structure and defects of metallurgical origin (axial looseness). In order to work out a cast structure and forge the axial looseness of an ingot, forgings for special purposes must be made with a forging ratio larger than 2.5...3.0. The predefined degree of deformation of the cast billet could be provided only when using the operation of ingot upsetting. The upsetting operation for cylindrical billets does not contribute to the closure of axial defects in forge ingots. It is a relevant field of research to improve the upsetting operation through the preliminary profiling of a cylindrical workpiece [1], which would make it possible to alter the stressed-strained state of a billet's metal and would contribute to welding internal defects.

2. Literature review and problem statement

Paper [1] analyzed different forging techniques for forgings of special purpose. It was found that these forging techniques differ in the type of the applied forge operations, thermomechanical deformation modes, and the use of specialized forge tools [2]. The paper failed to address the issue on improving the quality of large forgings by employing the new schemes of deformation. In addition, there are no techniques that would contribute to welding the internal defects during deformation.

It was established in paper [3] that there has lately been a significant increase in the need for large forgings, which are manufactured using the upsetting operation. Control over such parts is executed based on the mechanical properties, macrostructure, and residual stresses. It was found that the existing technological processes of forging large forge pieces do not ensure a stable high quality. However, the paper does not propose any new upsetting techniques, which would improve the quality of large forgings. Thus, it is required to develop new deformation techniques that would promote the welding of internal defects inside ingots.

The research reported in paper [4] made it possible to establish that the elimination of the axial porosity in an ingot requires its preliminary broaching. The paper suggested a parameter to assess the degree of closure of defects during forging, which takes into consideration the stressed state of the billet at upsetting. It was found that upsetting along the axis of an ingot without preliminary broaching does not reduce the axial looseness. However, the authors did not investigate the effect of the geometry of a deforming tool on the uniformity of working out the structure of forgings. In turn, the uniformity of working out the structure of a forging determines the anisotropy of mechanical properties of the manufactured part.

The magnitude of deformation at forging is the main factor that defines the working out of the structure of a forging and its mechanical properties, as it was established in paper [5]. However, comparison of different variants of technological processes for making forgings should be based on data on the distribution of the deformation intensity in a forging's cross-section. This was not fulfilled in paper [5] and could be a task for the further research in order to improve the technological processes when manufacturing parts with special purposes.

Excessive expansion of the liquation zone in the middle part of an ingot in the process of upsetting could be the cause of unsatisfactory quality of the part after machining [6]. However, authors of paper [6] did not study the impact of profiling a workpiece on a change in the stressed-strained state (VAT) during upsetting process.

The research reported in papers [7, 8] made it possible to establish that upsetting is used to work put a cast structure in order to improve impact viscosity and lower the anisotropy of mechanical properties. However, research results in papers [7, 8] showed a significant reduction in the uniformity of deformation distribution in the process of upsetting. The paper fails to propose any techniques that would enhance the uniformity of deformation distribution, which is the main direction of improving the quality of large forgings that requires conducting further research.

Authors of articles [9, 10] found that the upsetting operation is employed as an additional operation, intended to increase the forging ratio, rather than to work out the internal structure of a metal. However, the researchers did not suggest any new broaching techniques instead of the upsetting operation.

Upsetting with broaching ensures the high uniformity of deformation distribution along the axis of a workpiece, in comparison with the broaching scheme using the cut-out strikers as shown in paper [11]. That confirms the efficiency of applying the upsetting operation. However, authors of paper [11] did not investigate SSS in the process of upsetting profiled workpieces, which could also improve the effectiveness of combining the operations of broaching and upsetting.

In order to design new technological processes for manufacturing workpieces from ingots, it is necessary to have information on the workpiece's SSS and strength parameters during forging process [12]. At present, the theory of pressure treatment of metals employs a number of methods for determining SSS, shape-formation, and the deformation force parameters [13]. The distribution of SSS inside the body of workpiece during forging is considerably affected by the distribution of temperatures. In this regard, it is necessary to apply such methods to analyze a change in shape, which, taken together, account for the effect of temperatures and deformations on the stressed state of a workpiece's metal.

A modern theoretical method to study processes of pressure treatment is the finite element method (FEM) [14]. This method is used for determining SSS of a workpiece's metal. Development of new technological forging processes is impossible without using FEM [15]. Therefore, this method is appropriate for the investigation of forging processes.

Research into the dynamics of forging the axial looseness is reported in paper [16]. Designing the new technological forging processes when making forgings with special purposes requires information on the dynamics of forging the axial defects in an ingot at deformation according to new schemes. Experimental methods are used to study a metal's SSS applying both the field forgings and small models. When studying the deformed state, scientists have widely used a method of coordinate grids [17]. Therefore, this research method could be employed to verify results of the deformation distribution obtained using FEM [18].

In order to devise recommendations on the design of technological forging processes when making forgings with special purposes, it is necessary to establish SSS of workpieces during deformation. To conduct such a study, it is expedient to apply methods that make it possible to simulate the processes of forging at sufficient precision. These methods include FEM, which has proven to be a precise tool for conducting research and makes it possible to obtain results with a high degree of probability [19].

At present, still unresolved are the issues on improving technological forging processes when making forgings with special purposes, which would enhance the quality of the manufactured goods. A technique for upsetting cylindrical workpieces has been employed industrially. This method is characterized by the unfavorable SSS in a workpiece's metal during upsetting, which leads to the appearance of internal breaks and cracks.

An alternative to upsetting cylindrical workpieces is the preliminary formation of concave facets at a workpiece [20, 21]. A change in the cross-section of a workpiece by forming the concave facets will change the workpiece's metal SSS during upsetting. Concave facets of a workpiece will ensure the support of metal at deformation, which would contribute to a decrease in the level of tensile stress in the body of a workpiece. That would make it possible to exclude crack formation and to reduce the percentage of defects. Longitudinal concave facets can be easier obtained at a workpiece, making the technique simpler in implementation.

In this regard, it is necessary to undertake a research that would establish the effective profile of a workpiece with concave facets, which will contribute to the closure of internal defects of ingots.

3. The aim and objectives of the study

The aim of this work is to design a technique, which would contribute to forging the axial defects and to better working out the structure of a metal in the bulk of a workpiece based on the application of the new technique for upsetting the workpieces with concave facets, which would improve the quality of large forgings for special purposes.

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

– to assess the impact of the geometry of workpieces with concave facets on the stressed-strained state and the forging of axial defects in the process of upsetting, which would establish the effective deformation scheme;

– to test the results derived theoretically by conducting an experimental research into a change in the dimensions of axial defects during profiling and upsetting the workpieces with concave faces;

– to verify the new technological processes when using the upsetting of workpieces with concave facets under industrial conditions.

4. Procedure for studying the process of upsetting workpieces with concave facets

4. 1. Procedure of theoretical research

We have examined the process of upsetting workpieces with concave facets over-using the finite element simulation employing the software DEFORM 3D. The results of calculations are: the distribution of deformations and stresses in the body of a workpiece, as well as the change in the shape and dimensions of the axial defect during upsetting. The degree of deformation of a workpiece at upsetting was 50 %, as a recommended magnitude to obtain sufficient working out of a metal's structure [20]. A workpiece for the theoretical research had the following geometrical parameters: diameter of protrusion D=1.500 mm, and length L=3.750 mm. Diameter of the axial artificial defect d_0=0.1D (Fig. 1), which simulates the maximally permissible axial looseness in ingots. Prior to upsetting, the workpiece had concave facets with an angle α equal to 120° (Fig. 1). Relative depth of the concave facets of the workpiece (d/D) varied in the range of 0.75; 0.80; 0.85. Material of the workpiece is steel 34HNM, initial temperature for conducting the process is 1.200 °C, friction coefficient is 0.35, the grid is composed of 60,000 elements, the motion speed of a deforming tool is 20 mm/s [21–23].

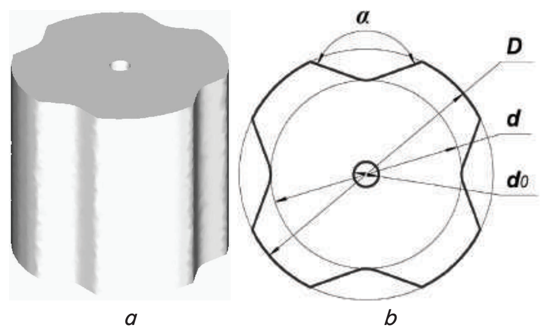


Fig. 1. Workpieces with concave facets: *a* – 3D-model; *b* – sketch of the workpiece

In order to determine an indicator of the stressed state in the axial zone, we marked a reference point in the middle of the height of the workpiece in which we monitored the mean stresses and the intensity of stresses. The indicator of the stressed state was determined from formula:

$$\Pi_\sigma = \frac{3\sigma_m}{\sigma_i},$$

where σ_m is the mean stresses, MPa; σ_i is the intensity of stresses, MPa.

4. 2. Procedure of experimental research

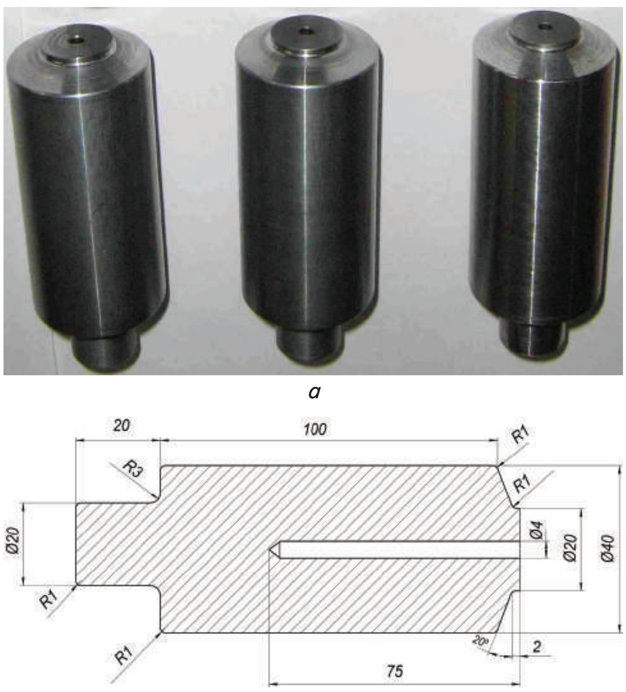
We have devised a special procedure for the non-destructive testing of the measurements of dimensions of the axial defect in order to estimate the impact of the process of upsetting workpieces with concave facets on the closure of internal defects. The procedure implied drilling an axial opening (Fig. 2, *a*) with a diameter of 10 % of the diameter of the lead workpiece [20]. The resulting opening was connected by means of a flexible tube with a measuring laboratory volumeter. The obtained system was filled with water. A change in the volume of a defect in the process of upsetting the workpiece with concave facets leads to a change in the level of the fluid in the volumeter. Based on the volume of the pressed-out fluid and the current height of the workpiece, we determined the average diameter of the defect [21]. Diameter of the lead workpieces is 50 mm, diameter of the opening is 5 mm. Cylindrical workpieces were preliminary deformed by concave strikers with an angle of 120° (Fig. 2, *b*) in order to form the concave facets. Deformation at profiling the workpiece was 15; 20; and 25 %, corresponding to the depth of the concave facets (d/D) 0.75; 0.80; 0.85.

We tested results of the mechanism for forging a defect on lead samples by conducting an experiment using models made of steel 34HNM (Fig. 3, *a*). Axial looseness of the ingot was modeled by the opening with a diameter of 4 mm (Fig. 3, *b*).

The samples (Fig. 3, *a*) were heated in an electric furnace to a temperature of 1.200 °C and deformed by concave strikers, followed by the upsetting of the obtained workpieces by flat plates.

a b

Fig. 2. Lead workpieces and tooling for experimental research: *a* – samples with axial defect; *b* – tools for profiling them



a

b

Fig. 3. Steel workpieces for experimental research: *a* – samples with axial defect; *b* – sketch of workpieces

5. Results of theoretical research into the process of upsetting workpieces with concave facets

5. 1. Thermal state of the workpiece during upsetting

Development of a new technological process of forging is impossible without studying the thermal state of a workpiece in the process of upsetting workpieces of the new shape. The distribution of temperature in the body of a workpiece affects the force and deformation modes, as well as SSS. Fig. 4 shows the temperature distribution after upsetting the workpiece with concave facets by the 50 % flat plates.

By analyzing the scheme of upsetting workpieces with different relative depths of concave facets, we have established that the temperature of the workpiece in the process of deformation is within the specified temperature range of forging (750°...1,200°). The distribution of temperatures in the examined schemes differs by 10...15 % at most.

5. 2. Closure of axial defects

The results of changes in the dimensions and shape of the axial defect in the process of upsetting workpieces with a different depth of concave facets (d/D) are shown in Fig. 4. By analyzing the obtained results of upsetting the workpieces with concave facets, it was found that all examined variants demonstrate the closure of the defect in the middle of the height of the workpiece. The intensity of the defect closure is larger when upsetting workpieces with a depth of concave facets of d/D=0.85 (Fig. 4, *c*).

Quantitative comparison of the degree of the axial defect closure after upsetting, by 50 %, the workpieces with a different depth of concave facets is shown in Fig. 5. The average diameter of the axial defect, computed based on its volume and the height of the upset workpiece, depends on the depth of the concave facets of the workpiece. The depth of the concave facets exceeding 20 % (d/D=0.75...0.80) does not contribute to forging the axial defects in the workpiece during upsetting (Fig. 5). For an angle of the concave facets of 120°, an increase in their depth leads to an increase in the degree of closure of the defect.

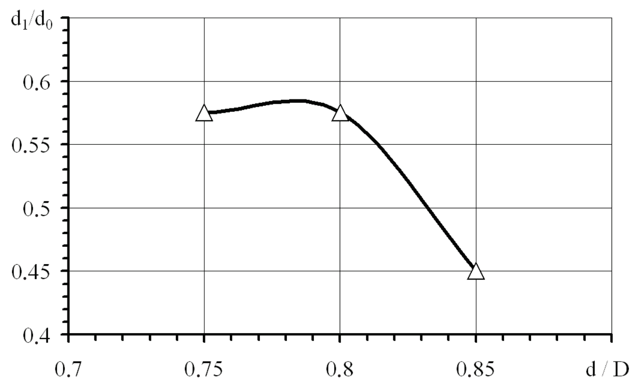
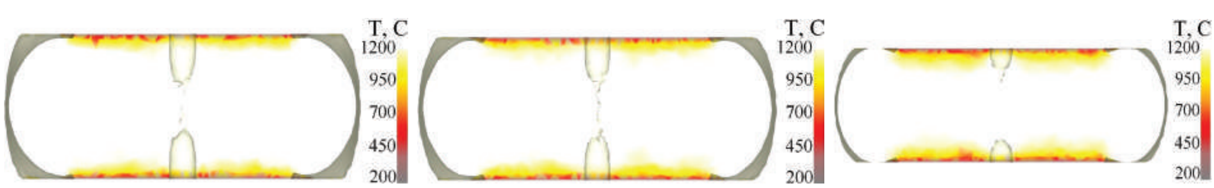


Fig. 5. A change in the relative diameter of a defect depending on the depth of concave facets (d/D) after upsetting by 50 %

In order to devise effective technological modes of forging, it is necessary to establish patterns in the dimensions of axial defects due to a deformation degree at upsetting. In this regard, in order to quantify the degree of closure of an axial defect, we calculated data on a change in the magnitude of relative diameter of a defect on the degree of deformation (Fig. 6).



a b c

Fig. 4. Closure of the axial defect and temperature distribution after upsetting workpieces with concave facets: *a* – d/D=0.75; *b* – d/D=0.80; *b* – d/D=0.85

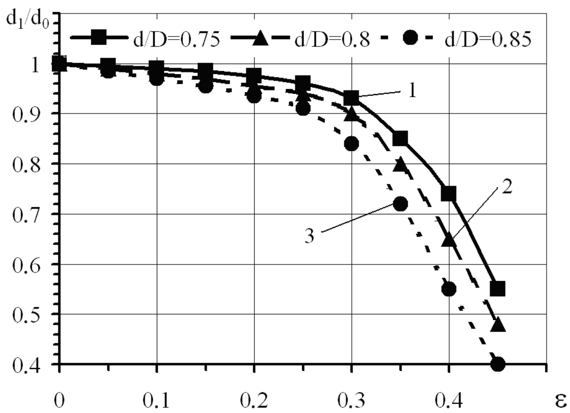


Fig. 6. Relative diameter of a defect depending on the degree of deformation for different depths of concave facets: 1 – *d/D*=0.75; 2 – *d/D*=0.80; 3 – *d/D*=0.85

A general pattern for the obtained results of modelling for different profiles of workpieces: the closure of defects starts after upsetting by 15 %; the intensity of the closure of an axial defect for different profiles of workpieces differs by 10 % at most. For the workpieces of d/D=0.85 at a degree of deformation of 40 %, the lowest value of relative defect d_1/d_0 is 0.6 (which means that the closure of the axial defect is achieved by 40 %). The recommended degree of deformation, at which the forging of the axial defects would occur, is not less than 50 %.

5. 3. The stressed-strained state in the process of upsetting

Fig. 7 and Fig. 8 show results of the distribution of intensity of logarithmic deformations and average stresses in the longitudinal section of a workpiece after upsetting by 50 %. Maximal deformations (e_i>1.0) are localized in the axial zone in the middle of the height of the workpiece, while minimal deformations ($e_i \approx 0$) are in the end zones of the workpiece that are in contact with the tool. The zone of plastic deformations is qualitatively and quantitatively identical for different parameters of the concave cross-section. That makes it possible to draw a conclusion about the insignificant influence of the cross-sectional shape of a workpiece with concave facets on the deformed state (Fig. 7). However, upsetting the workpieces with concave facets leads to a change in the stressed state of a workpiece's metal in the axial zone. The maximal compressing stress (–70 MPa) occur at the location of the defect at a depth of concave facets of 15 % (Fig. 8, *c*).

An increase in the depth of concave facets helps reduce the level and area of the zone of compressing average stresses. The examined schemes are characterized by the dominance of compressing stressed in the body of a workpiece, except for a peripheral side zone that has the shape of a barrel (Fig. 8).

Fig. 9 shows results of the distribution of intensity of logarithmic deformations (e_i) for the height of a workpiece (H) after upsetting workpieces by 50 % for different depths of the concave facets. The uniform distribution of deformations for height is ensured by a workpiece with the depth of concave facets of d/D=0.85 (Fig. 9, curve 3).

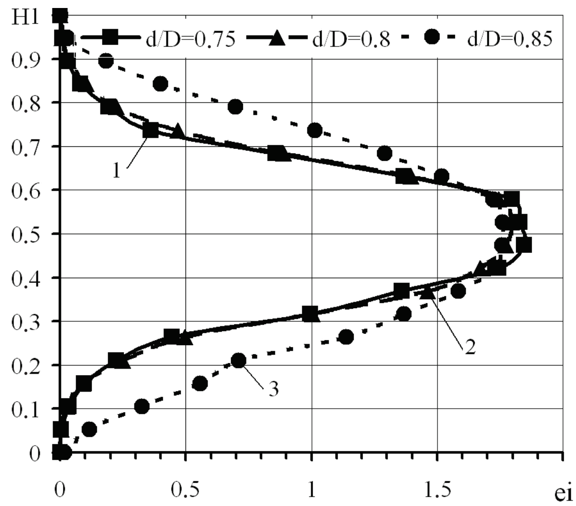
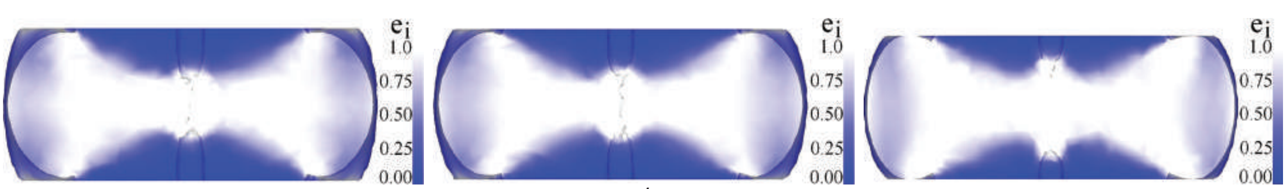


Fig. 9. Distribution of the intensity of logarithmic deformations for the height of a workpiece after upsetting by 50 % at different depths of the concave facets: 1 – *d/D*=0.75; 2 – *d/D*=0.80; 3 – *d/D*=0.85

An analysis of a change in the shape of an axial defect that we performed has made it possible to establish that the maximum intensity of its closure occurs at upsetting the workpieces with a ratio of d/D=0.85. These results are explained by the respective stressed state in the axial zone of a workpiece in the process of upsetting. An indicator of the stressed state diagram (Π_σ) with the minus sign indicates the dominance of compressing stresses in the axial zone of the workpiece, which contributes to welding the axial defects (Fig. 10).



a *b* *c*

Fig. 7. Distribution of the intensity of deformations when upsetting workpieces with concave facets: *a* – *d/D*=0.75; *b* – *d/D*=0.80; *c* – *d/D*=0.85

a *b* *c*

Fig. 8. Distribution of average stresses when upsetting workpieces with concave facets: *a* – *d/D*=0.75; *b* – *d/D*=0.80; *c* – *d/D*=0.85

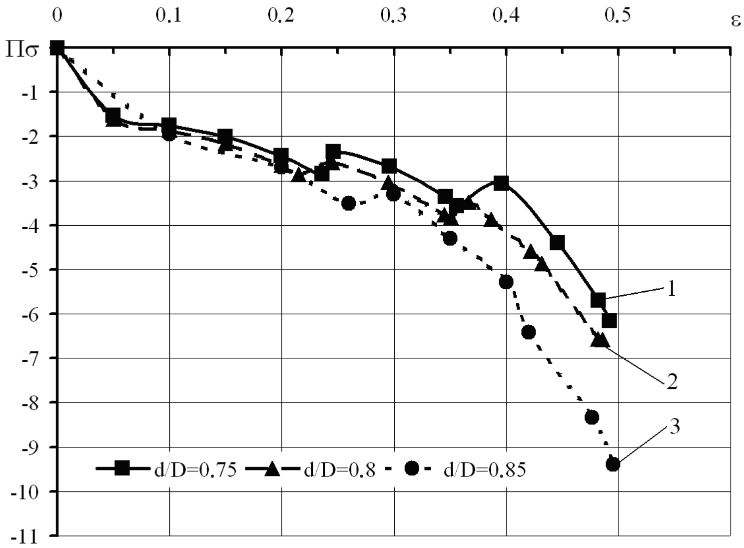


Fig. 10. The indicator of the stressed state in the process of upsetting workpieces with different depths of concave facets: 1 – $d/D=0.75$; 2 – $d/D=0.80$; 3 – $d/D=0.85$

A general pattern in the process of upsetting workpieces with concave facets is an increase in the level of compressing stresses in the axial zone with an increase in the degree of deformation (Fig. 10).

One can note that the workpiece of parameters $d/D=0.85$ demonstrates a high level of compressing stresses ($\Pi_\sigma=-9.4$) at the degree of compression of $\varepsilon=0.5$.

6. Results of experimental research into the process of upsetting the workpieces with concave facets

6. 1. Closure of axial defects in lead workpieces

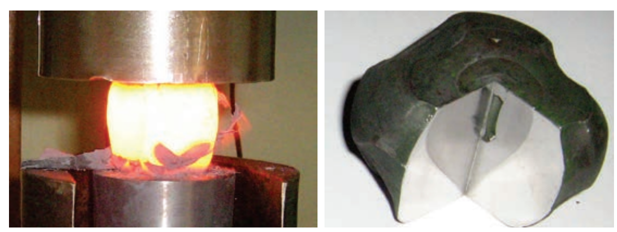
A workpiece after upsetting, with the connected flexible hose to register the displacement of fluid, is shown in Fig. 11, *a*. The results of investigating the degree of the closure of axial defects in the process of upsetting lead workpieces with varying depths of concave facets are shown in Fig. 11, *b*.

An angle of the concave facets of 120° promotes the forging of an axial defect in the process of upsetting (Fig. 11, *b*). This is explained by an increase in the level of compressing stresses in the central zone of a workpiece when upsetting workpieces with concave facets, as it was established in the course of the theoretical study (Fig. 10).

The results obtained have allowed us to establish that the intensive closure of an axial defect in the process of upsetting workpieces with concave facets occurs when deformation ε exceeds 25 % (Fig. 11, *b*). Upon upsetting by 60 %, the average diameter of a defect decreases by 65 % (Fig. 11, *b*). The results obtained coincide with the data acquired from the theoretical study (Fig. 6).

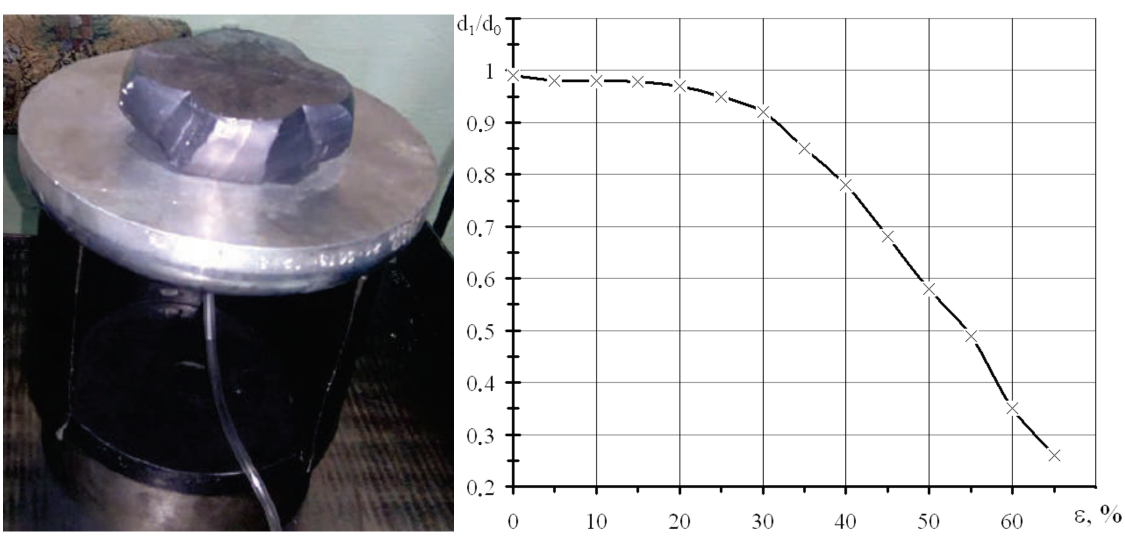
6. 2. Closure of axial defects in steel workpieces

The obtained results regarding the change in shape and the closure of axial defects for lead models were verified by investigating steel samples (steel 34CrNiMo). After heating the workpieces to a temperature of 1,200°, we profiled them, using the concave strikers with an angle of 120°, at a total compression over two runs equal to 20 %. Upon profiling, the upsetting by 50 % was performed (Fig. 12, *a*). Upon the upsetting and cooling, we cut the workpieces in order to measure an axial defect (Fig. 12, *b*).



a *b*

Fig. 12. Experimental research: *a* – deformation of heated workpieces; *b* – shape of the axial defect upon upsetting a workpiece with concave facets



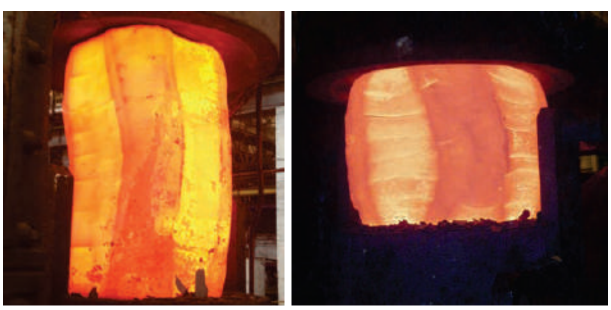
a *b*

Fig. 11. Results of experimental research: *a* – a workpiece upon upsetting; *b* – a change in the dimensions of an axial defect in the process of upsetting

After grinding and polishing the plane of the cut, we examined the traces of the axial defect after upsetting. The upsetting of workpieces with concave facets at an angle of 120° with a compression degree of 20 % made it possible to establish a degree of forging the axial opening (Fig. 12, *b*). The results obtained allowed us to establish that, as regards the examined scheme, the upsetting is followed by a partial closure of the axial defect, deformed by the strikers with an angle of 120° (Fig. 12, *b*).

6. 3. Implementation of the process of upsetting the workpieces with concave facets under industrial conditions

The difference between the new technological process and the standard one is the application of the operation for profiling an ingot by a concave striker at the bottom flat plate with a swaging of 150 mm (20 %) in order to obtain a workpiece with the concave facets. Upon upsetting with flat plates (Fig. 13), the workpiece acquires a cross-section close to a square, with a side of ≈1.850 mm (the degree of deformation $\varepsilon \approx 5$ %). After the upsetting, the side surface of the workpiece does not demonstrate a barrel-like shape, indicating a change in SSS, and contributing to an increase in the level of compressing stresses at the side surface and in the axial zone of the workpiece. The result is the absence of crack formation at the side surface in the process of upsetting. Subsequent operations are similar to the standard technological process. For the new technological process, the magnitude of the forge factor (a basic indicator of the quality of a would-be forging and the cost of forging) reduced from 2.28 to 1.96. The obtained forgings were tested by ultrasonic control (USC).



a *b*

Fig. 13. Implementation of the new technique for upsetting the workpieces with concave facets with a weight of 30 tons: *a* — prior to upsetting; *b* — upon upsetting

Based on the USC results, we detected a cluster of defects with an equivalent diameter of up to 3.0 mm. We have not identified any internal defects with an equivalent diameter over 2.0 mm in the main part of the forging. The USC results for the second forging, made using the same technology, are similar. In the axial area of the forging, there are single defects with an equivalent diameter less than 4.0...6.0 mm, which is much less than the permissible dimensions of defects required by the customer.

7. Discussion of results of studying the process of upsetting workpieces with concave facets

The qualitative and quantitative similarity of results for the distribution of temperatures and the deformations of the workpiece in the process of upsetting can be explained by the same volume of the workpiece's metal and the same boundary conditions for deformation.

The closure of defects in the middle height of the workpiece is due to the occurrence of compressing stresses in this part (Fig. 8). The closure of axial defects after upsetting by 15...25 % for the examined schemes of deformation is explained by the emergence of maximal deformations in the axial zone of the workpiece (Fig. 7).

The maximal intensity of the closure of the defect for workpieces with ratio $d/D=0.85$ is explained by the emergence of maximal compressing stresses in the axial zone of the workpiece (Fig. 10). The increase in the level of compressing stresses in the axial area at an increase in the degree of deformation (Fig. 10) is due to the occurrence of intensive deformations in the body of the workpiece (Fig. 7).

The benefits of the proposed new method for upsetting the workpieces with concave facets:

– The closure of axial defects starts after upsetting by 15 %. Following the upsetting by 40 %, the lowest value for relative defect d_1/d_0 is 0.6 for the depth of concave facets $d/D=0.85$. A workpiece with a depth of concave facets of $d/D=0.85$ and angle $\alpha=120°$ provides for a high level of compressing stresses ($\Pi_\sigma=-9.4$) at the degree of deformation $\varepsilon=50$ %. Moreover, the maximal values for the intensity of deformations (e_i) are also characteristic of these parameters. That would ensure the intensive closure of internal defects as compared to the upsetting of cylindrical workpieces.

– The maximal compressing stresses occur at the location of a defect at a depth of the concave facets of 15 % (Fig. 8, *c*), which would positively affect the welding of internal axial defects in a workpiece under small degrees of profiling.

– An increase in the degree of deformation at upsetting leads to an increase in the level of compressing stresses in the axial zone (Fig. 10), which contributes to welding the internal defects compared to the upsetting of cylindrical workpieces.

– The USC results confirm the high effectiveness of the scheme for upsetting a workpiece with concave facets when forging the axial defects in an ingot. This improves the quality of forgings for special purposes.

– Upon upsetting, the side surface of a workpiece does not reveal any significant barrel-like shape, indicating the change in SSS and the increase in the level of compressing stresses. The result is the absence of crack formation at the side surface in the process of upsetting.

Disadvantages of the proposed new method for upsetting workpieces with concave facets:

– increasing the depth of concave facets of a workpiece reduces the level of dimensions of the zone of compressing middle stresses;

– the examined schemes are characterized by a low level of compressing stresses in the process of upsetting at the side surface, which has the shape of a barrel (Fig. 8).

Our research is an important scientific and practical advancement and could prove useful for the theory and practice of forging processes involving large forgings.

From a practical point of view, the revealed mechanism for the closure of axial defects in ingots at upsetting makes it possible to define conditions for applying the proposed deformation technique in the forging technology when manufacturing large forgings for special purposes. The applied aspect of exploiting the result obtained is a possibility to improve the technological process to fabricate parts for special purposes in the energy and heavy machine building.

The chosen concept of improving the quality of large forgings by upsetting the workpieces with concave facets is new and has been confirmed by our research. However, the research results established that the complete closure of the axial defect is not achieved for workpieces with an angle of the concave facets of 120°. Therefore, the further additional research must be conducted in order to establish the impact of angle of the concave facets on the mechanism of closure of axial defects.

8. Conclusions

1. It was established that for the closure of internal defects and for the distribution of SSS when upsetting the workpieces with concave faces, the crucial parameter is the ratio between dimensions d/D. An axial defect in the process of upsetting closes more intensively at a depth of the concave facets of d/D=0.8...0.85. These parameters are recommended to be effective in terms of improving the quality of the axial zone of an ingot in the process of upsetting.

2. Based on experimental research, it was found that the closure of defects starts upon upsetting the workpieces with concave facets by 25 %. The recommended degree of deformation, at which the forging of axial defects would occur, is not less than 50 %. Following the upsetting by 60 %, the average diameter of a defect reduces by 65 %.

3. We have designed and implemented the new technological forging processes for manufacturing large forgings for special purposes using the upsetting of workpieces with concave faces. The forgings that we obtained matched the technical specifications from the customer. The USC results confirm the high efficiency of the scheme for upsetting a workpiece with concave facets when forging and welding the axial defects in an ingot. Specifically, dimensions of the axial defects decreased from 7...8 mm for a standard technology to a maximum of 4...6 mm for the proposed technology.

References

1. Research on Charging Combination Based on Batch Weight Fit Rule for Energy Saving in Forging / Baiqing Z., Haixing L., Yifei T., Dongbo L., Yong X. // Mathematical Problems in Engineering. 2015. Vol. 2015. P. 1–9. doi: https://doi.org/10.1155/2015/531756
2. Ameli A., Movahhedy M. R. A parametric study on residual stresses and forging load in cold radial forging process // The International Journal of Advanced Manufacturing Technology. 2006. Vol. 33, Issue 1-2. P. 7–17. doi: https://doi.org/10.1007/s00170-006-0453-2
3. Dobrzański L. A., Grajcar A., Borek W. Influence of hot-working conditions on a structure of high-manganese austenitic steels // Journal of Achievements in Materials and Manufacturing Engineering. 2008. Vol. 29, Issue 2. P. 139–142. URL: http://jamme.acmsse.h2.pl/papers_vol29_2/2924.pdf
4. Development of forging process design to close internal voids / Kakimoto H., Arikawa T., Takahashi Y., Tanaka T., Imaida Y. // Journal of Materials Processing Technology. 2010. Vol. 210, Issue 3. P. 415–422. doi: https://doi.org/10.1016/j.jmatprotec.2009.09.022
5. Strain function analysis method for void closure in the forging process of the large-sized steel ingot / Chen K., Yang Y., Shao G., Liu K. // Computational Materials Science. 2012. Vol. 51, Issue 1. P. 72–77. doi: https://doi.org/10.1016/j.commatsci.2011.07.011
6. Internal void closure during the forging of large cast ingots using a simulation approach / Lee Y. S., Lee S. U., Van Tyne C. J., Joo B. D., Moon Y. H. // Journal of Materials Processing Technology. 2011. Vol. 211, Issue 6. P. 1136–1145. doi: https://doi.org/10.1016/j.jmatprotec.2011.01.017
7. Sang B., Kang X., Li D. A novel technique for reducing macrosegregation in heavy steel ingots // Journal of Materials Processing Technology. 2010. Vol. 210, Issue 4. P. 703–711. doi: https://doi.org/10.1016/j.jmatprotec.2009.12.010
8. Physical modeling of the upsetting process in open-die press forging / Erman E., Medei N. M., Roesch A. R., Shah D. C. // Journal of Mechanical Working Technology. 1989. Vol. 19, Issue 2. P. 195–210. doi: https://doi.org/10.1016/0378-3804(89)90004-1
9. Kitamura K., Terano M. Determination of local properties of plastic anisotropy in thick plate by small-cube compression test for precise simulation of plate forging // CIRP Annals. 2014. Vol. 63, Issue 1. P. 293–296. doi: https://doi.org/10.1016/j.cirp.2014.03.038
10. Mitani Y., Mendoza V., Osakada K. Analysis of rotor shaft forging by rigid-plastic finite element method // Journal of Materials Processing Technology. 1991. Vol. 27, Issue 1-3. P. 137–149. doi: https://doi.org/10.1016/0924-0136(91)90049-k
11. Simulation of 42CrMo steel billet upsetting and its defects analyses during forming process based on the software DEFORM-3D / Zhang Z. J., Dai G. Z., Wu S. N., Dong L. X., Liu L. L. // Materials Science and Engineering: A. 2009. Vol. 499, Issue 1-2. P. 49–52. doi: https://doi.org/10.1016/j.msea.2007.11.135
12. Vafaeesefat A. Finite Element Simulation for Blank Shape Optimization in Sheet Metal Forming // Materials and Manufacturing Processes. 2011. Vol. 26, Issue 1. P. 93–98. doi: https://doi.org/10.1080/10426914.2010.498072
13. Thermal-Elastic-Plastic Simulation of Internal Stress Fields of Quenched Steel 40Cr Cylindrical Specimens by FEM / Liu L., Liao B., Li D., Li Q., Wang Y., Yang Q. // Materials and Manufacturing Processes. 2011. Vol. 26, Issue 5. P. 732–739. doi: https://doi.org/10.1080/10426910903367428
14. Numerical and experimental investigations on the extension of friction and heat transfer models for an improved simulation of hot forging processes / Behrens B.-A., Alasti M., Bouguecha A., Hadifi T., Mielke J., Schäfer F. // International Journal of Material Forming. 2009. Vol. 2, Issue S1. P. 121–124. doi: https://doi.org/10.1007/s12289-009-0618-2

15. Just H. Blick in das Innere eines Freiformschmiede-prozesses // Stahl und Eisen. 2006. Issue 12. P. 70–72.
16. Zhbankov I. G., Perig A. V., Aliieva L. I. New schemes of forging plates, shafts, and discs // The International Journal of Advanced Manufacturing Technology. 2015. Vol. 82, Issue 1-4. P. 287–301. doi: https://doi.org/10.1007/s00170-015-7377-7
17. Zhbankov I. G., Markov O. E., Perig A. V. Rational parameters of profiled workpieces for an upsetting process // The International Journal of Advanced Manufacturing Technology. 2014. Vol. 72, Issue 5-8. P. 865–872. doi: https://doi.org/10.1007/s00170-014-5727-5
18. Markov O. E. Forging of large pieces by tapered faces // Steel in Translation. 2012. Vol. 42, Issue 12. P. 808–810. doi: https://doi.org/10.3103/s0967091212120054
19. Development of a new process for forging plates using intensive plastic deformation / Markov O. E., Perig A. V., Markova M. A., Zlygoriev V. N. // The International Journal of Advanced Manufacturing Technology. 2015. Vol. 83, Issue 9-12. P. 2159–2174. doi: https://doi.org/10.1007/s00170-015-8217-5
20. A new process for forging shafts with convex dies. Research into the stressed state / Markov O. E., Perig A. V., Zlygoriev V. N., Markova M. A., Grin A. G. // The International Journal of Advanced Manufacturing Technology. 2016. Vol. 90, Issue 1-4. P. 801–818. doi: https://doi.org/10.1007/s00170-016-9378-6
21. Development of forging processes using intermediate workpiece profiling before drawing: research into strained state / Markov O. E., Perig A. V., Zlygoriev V. N., Markova M. A., Kosilov M. S. // Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2017. Vol. 39, Issue 11. P. 4649–4665. doi: https://doi.org/10.1007/s40430-017-0812-y
22. Aliev I., Zhbankov I., Martynov S. Forging of shafts, discs and rings from blanks with inhomogeneous temperature field // Journal of Chemical Technology and Metallurgy. 2016. Vol. 51, Issue 4. P. 393–400.
23. Markov O. E., Oleshko M. V., Mishina V. I. Development of Energy-saving Technological Process of Shafts Forging Weighting More Than 100 Tons without Ingot Upsetting // Metalurgical and Mining Industry. 2011. Vol. 3, Issue 7. P. 87–90. URL: http://www.metaljournal.com.ua/assets/Uploads/attachments/87Markov.pdf