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DEVELOPMENT OF A NEW PROCESS FOR EXPANDING STEPPED TAPERED RINGS

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Досліджено новий спосіб розкочування великогабаритних конусних кілець зі ступінчастим профілем. Запропонований спосіб полягає у деформуванні заготівки з уступом східчастим бойком. Запропонована методика проведення досліджень методом скінчених елементів. Методика призначена для визначення залежностей напружено-деформованого стану та формозміна заготівки у процесі розкочування східчастим бойком. Змінними параметрами були відносна висота виступу східчастих заготівок, яка варіювалась в інтервалі 2,2...2,5. На основі скінчено-елементного моделювання були встановлені: розподіл інтенсивності деформацій у перерізі поковки після розкочування ступінчастим бойком. Визначалась конусність поковок, яка утворюється при розкочуванні за даним способом. Результати скінчено-елементного моделювання перевірялися експериментальними дослідженнями на свинцевих та сталевих зразках. Була запропонована методика проведення експериментальних досліджень. Скінчено-елементне дослідження дозволило встановити, що розкочування ступінчастим бойком призводить до утворення поковки конусної форми. Це пояснюється тим, що при обтисканні уступу йде більша тангенціальна деформація кільцевої заготівки в зоні уступу, ніж зоні виступу внаслідок різної висоти ступінчастої заготівки. Результати скінчено-елементного моделювання були підтверджені експериментами в лабораторних умовах на свинцевих та сталевих зразках. Збільшення діаметру виступу заготівок призводить до збільшення ступеня деформації виступу, що викликає збільшення діаметра отвору виступу. Аналіз макроструктури конусної кільцевої поковки зі ступінчастим профілем дозволив встановити, що при використанні операції розкочування ступінчастого кільця східчастим інструментом волокна структури повторюють форму деталі, що виключає їх перерізання при механічній обробці. В результаті досліджень було встановлено, що розкочування ступінчастих конусних заготівок можливе, це розширює технологічні можливості процесу розкочування великогабаритних поковок

Ключові слова: ступінчасте конусне кільце, розкочування, ступінчастий бойок, розподіл деформацій, формозміна, конусність

1. Introduction

Production of large-size forgings has ever increasing in recent years. It relates to the growth of power and number of electrical generating stations and heavy machinery [1]. Heavy and power engineering products include significant amounts of rings including tapered rings. Such shaped forgings are high-duty products subject to strict requirements to isotropy of mechanical properties, internal structure, etc. Most of the rings are made using expansion operations. Tapered rings are made currently by machining cylindrical thick-walled rings which leads to excess metal consumption caused by enormous machining allowances as well as reduced mechanical properties of the products because of cutting fibrous metal structure of forgings during machining.

One of the ways to improve manufacture of large-sized tapered rings with a stepped profile consists in the use of stepped hollow blanks (ingots) to obtain forgings with a shape repeating that of the final part. Hollow ingots can reduce work content in forging large-sized rings and cut metal waste due to the absence of piercing stage. Manufacture of stepped tapered rings requires application of special operations for forging hollow blanks (ingots). Making stepped tapered forgings which repeat the target part contour is an urgent scientific and technical problem. Its solution would eliminate cutting of fibrous metal structure and reduce metal wastage during machining.

2. Literature review and problem statement

The application of ingots with a new configuration is the main direction of improving manufacture of large-sized rings including tapered rings. Low quality of forge ingots is caused by internal defects of metallurgical origin present. When forging large-sized rings, these defects are fused and removed from the forging body. To date, there are various ways to improve quality of forging ingots. However, they have limitations and purposes. Therefore, at the first stage, it is necessary to consider ingots which are used for forging tapered rings with a stepped profile.

Examination of longitudinal and transverse sections of ingots reveals porosity and cracks in their central part. They have to be eliminated during the forging process [2, 3]. Axial porosity is one of typical defects of conventional ingots. It is accompanied by inclusions and macro-liquation [4]. According to the data obtained in [4], 3D modeling has made it possible to establish optimum temperature and crystallization rate to reduce axial porosity.

It was found in [5, 6] that the use of a cooled ingot sinkhead with a reverse taper increases depth of the shrink cavity and concentrates it along the axis which in turn reduces coefficient of metal utilization by 7 %. This can bring about internal defects in the forging body worsening quality of large-sized rings.

Results of forging of a reactor block from a conventional 190-ton ingot are described in [7]. The technology included sinking and piercing. After that, the blank was drawn on a tapered mandrel and expanded on a mandrel with the use of a narrow die. The ingot forging technology under study assumed two heating operations for sinking and piercing which have resulted in a significant rise of energy consumption for forging. Moreover, the paper lacks technological recommendations regarding the percent reduction obtained in one expanding pass as the main parameter of forging hollow blanks.

It is necessary that internal defects were concentrated in the center of the conventional ingot at the initial forging stage [8]. After that, the ingot is sunk to reduce height and increase diameter of the blank. This improves uniformity of deformation distribution and improves working of the structure. To eliminate defects in a large ingot by piercing, they must be located in the center of the ingot during the forging process. This requires improvement of forging processes in which the tool shape and size must be optimized. Based on improvement of the forging process, JWS Co. has manufactured a flanged shell from a 350-ton ingot.

It was found in [9] that the forgings made of hollow ingots simplify the ring forging process. Use of hollow ingots for the manufacture of annular forgings simultaneously with improvement of the product quality ensures a 25–30 % cut of metal consumption. However, in this case, porosity can be expected in the middle of the hollow ingot wall which will result in quality deterioration.

Sheffield Forgemasters Ltd. (USA) has introduced hollow ingots into the range of products [10] intended for forging rings. However, no recommendations on choosing optimal geometrical parameters of hollow blanks were given. Moreover, it was not specified how these parameters affect mechanical properties of the product and no recommendations concerning deformation conditions that provide the declared forging properties were given.

Creusot-Loire Industrie has established effect of internal defects in forging blanks on formation of cracks and developed optimal recommendations for making large forgings [11, 12]. The use of hollow ingots with controlled location of segregation zones is an effective solution for rings. However, the papers do not present the study results nor they give recommendations concerning parameters of the ring forging process. Information regarding ratio of the ingot dimensions which will reduce heterogeneity of chemical composition and amount of axial porosity would be especially useful.

The second stage consists in improving the processes of manufacture of large-sized stepped tapered forgings which would repeat the target part contour. This will make it possible to eliminate cutting of fibrous metal structure and reduce metal wastage during machining. These methods consist in the use of special forging operations or working tools. In this regard, it is necessary to establish effect of the operations and tooling on expanding of hollow forgings.

The demand for large-sized rings with diameter of up to 10 meters and height of up to 6 meters is explained by development of nuclear power plants [13]. Production of rings of such height would simplify the reactor design. To make rings with the specified dimensions, it is necessary to create special equipment for external expanding. Such expanding device must be driven by a hydraulic forging press. However, this equipment has limited technological capabilities.

The essence of the method described in [14] implies the installation of a special crossbar that serves as a die. The press force is transmitted between the movable tie-bar and this crossbar. A ring with a specified wall thickness is formed between the bottom tool and the tie-bar which is held and rotated by a mandrel [15]. However, the study did not give dimensions of the blank before expanding and information on how large reduction was per one circular pass.

A method of forging rings which consists in installing an additional hydraulic mechanism was proposed in [16]. There are no limits of the maximum ring size in this embodiment. However, it was not indicated how to make tapered rings with a stepped surface.

Analysis of studies [13–16] with the main idea consisting in the use of special tools and equipment for expanding large-sized rings has made it possible to establish that there is no detailed description of the expanding equipment design. Also, there are no recommendations regarding parameters of the blank and the deformation process such as deformation rate and the wall thickness achievable by forging.

Forged rings can be made either from conventional ingots using the process of piercing or from hollow ingots [17–19]. The need for upsetting and piercing conventional ingots requires large material and energy resources. To reduce metal consumption and weight of the ingots used to manufacture annular forgings, hollow ingots have been introduced which greatly simplifies forging procedure and reduces number of heating steps [20].

Analysis of published data [14–20] has made it possible to state that the problem associated with reduction of metal consumption and improvement of mechanical properties in production of tapered stepped rings has not been solved to date. This is explained by the fact that large machining allowances are specified for the tapered stepped parts. As a result, instead of tapered rings, cylindrical ones are used bringing about increased metal wastage and metal fibers cut during machining. That is why it is necessary to develop and study a new method for manufacture of large-sized tapered rings by forging.

3. The aim and objectives of the study

The study objective is to reduce metal consumption and expand technological capabilities when forging tapered hollow blanks based on development of new technological processes of expanding rings with a stepped surface.

To achieve this objective, the following tasks were set:

– choose methods and develop procedures for studying expanding of stepped tapered rings;

– conduct theoretical study of shape change and stress-strain state (SSS) of tapered blanks with a stepped profile;

– conduct experimental studies of the operation of expanding tapered rings with a stepped profile and establish dependences of the blank shape change on the ratios of initial blank dimensions and cross-section deformation rate;

– conduct macrostructure studies of forgings obtained by the new technology.

4. The procedure of studying the process of expanding tapered rings with a stepped profile

4. 1. Theoretical study of a stepwise expanding operation

The ring forging process was modeled by the finite element method (FEM). Distribution of the forging SSS and shape change during expanding were established in accordance with the modeling results. Boundary conditions of modeling the expanding process had the following values:

– initial temperature of the blank: 1,200 °C;

– the number of mesh elements: 80,000;

– the tool movement speed: 40 mm/s;

– the die and mandrel temperature: 100 °C;

– a Zibel friction coefficient: 0.7.

A 1,240 mm dia. mandrel was chosen as the bottom tool. Draft of the stepped forge die is shown in Fig. 1.

The protrusion and the wall were deformed simultaneously (Fig. 2, *a*). Each pressing stroke measured 60 mm in one circular pass. Following one reduction with the die, the blank was turned and further deformation was performed. This sequence of operations was repeated until required values of the distance between the tools corresponding to the forging wall thickness and deformation rate were reached.

The expanding process was carried out with the help of a stepped die in which the working surface (Fig. 1) repeats outside surface of the blank (Fig. 2, *b*). The difference between diameters of the protrusion and the wall was equal to the size of the die step and measured 275 mm. Relative diameter of the blank was 2.3 for the protrusion and 1.87 for the wall.

4. 2. The procedure used in conducting the experiments

As evidenced by numerous studies, the FEM method has a high accuracy in determining the SSS parameters including those for the processes of hot plastic deformation [22–25]. However, the FEM is a theoretical method and requires experimental verification of the results obtained [26].

Lead samples in a scale of 1:40 to the actual forging size were made for experiments. The samples were made by casting in a mold with a rod. A stepped die was made for expanding. The die with a total length of 130 mm had a 7 mm high step and a 40 mm long protrusion section. The mandrel had diameter of 30 mm. In order to obtain accurate dimensions and provide the necessary deformation rate, a set of 1 mm thick plates was used. Deformation was conducted on a 100 kN hydraulic press at deformation rate of 200 mm/min.

For macrostructure studies, experiments were performed on steel samples. Alloyed tool steel of KhVG grade was chosen as a material because it is widely used in the production of large forgings. Tools were also made for expanding: a stepped die and a mandrel (Fig. 3).

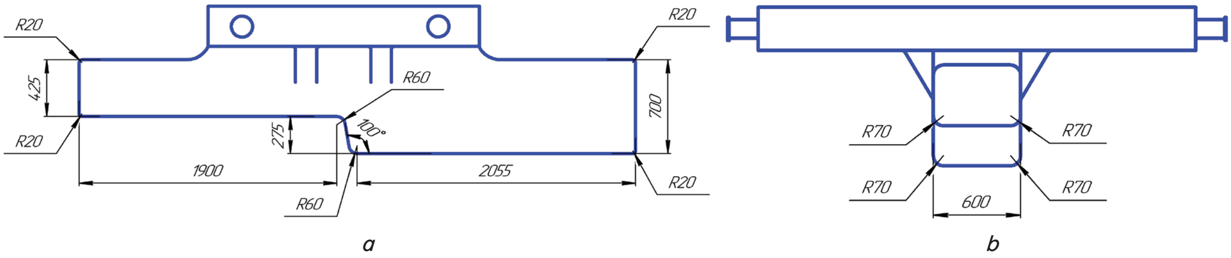


Fig. 1. Draft of the stepped die: front view (*a*); side view (*b*)

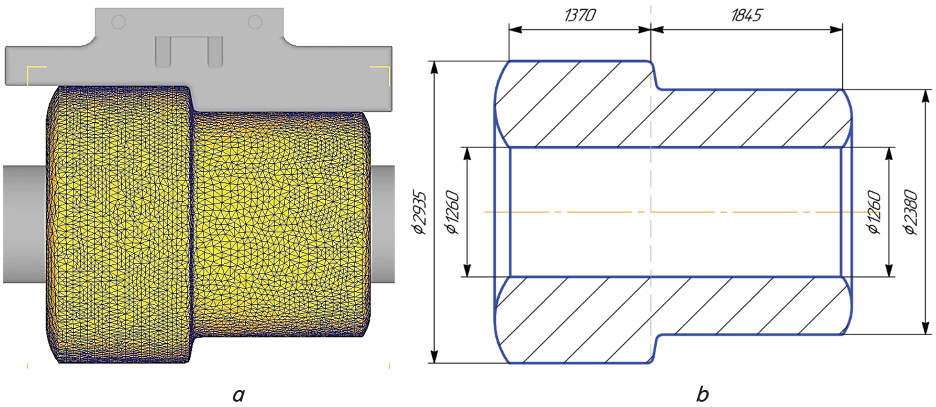
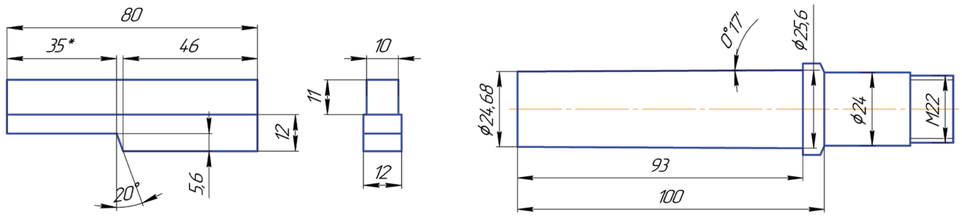


Fig. 2. The results of simultaneous expanding of the protrusion and the wall: design expanding model (*a*); draft of the blank for expanding (*b*)



a b

Fig. 3. Tools for experimental studies: stepped die (*a*); mandrel (*b*)

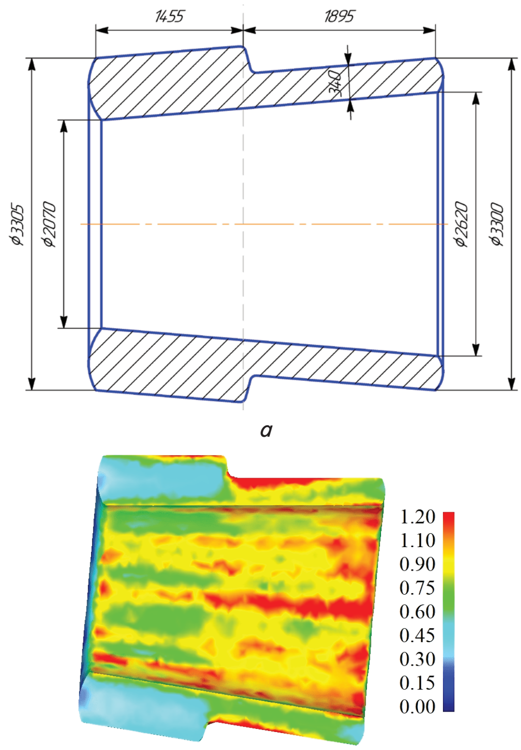
The samples were heated to 1,100 °C with holding time of 10 min in an electric oven. Reduction was 1 mm per pass, both during drawing and die expanding. A 25 mm dia. mandrel (Fig. 3, *b*) and dies of a corresponding profile were used for expanding.

5. Analysis of the forging expanding

The results obtained in the study have allowed us to find that the wall had diameter larger than that of the adjacent protrusion when the protrusion and the wall were shaped simultaneously (Fig. 4). In this case, deformation intensity in the protrusion was less than that in the wall. Maximum deformations in the wall were concentrated in the surface of contact of the blank with the tool. Intensity of deformation in the wall was large which indicates a high degree of working of this forging section. Different degrees of deformation can be explained by different thicknesses of the protrusion and the wall. The wall experienced a greater degree of relative deformation than the protrusion at the same pressure applied to the protrusion and the wall. Based on the simulation results, it was found that the largest strains were concentrated at the transition from the protrusion to the wall. The resulting forging had a taper at the wall deformation rate of 0.38. The taper constantly grew during expansion (Fig. 5) due to an increase in the wall inside diameter compared to that of the protrusion. The inside taper was affected both by the difference in diameters of the protrusion and the wall and forging time. The blank length did not change significantly after expanding, so we can conclude that its effect was negligible.

Dependence of the change in relative diameters of the protrusion bore, $d_{n.B}/L_n$, and the wall, $d_{n.y}/L_n$, on the protrusion deformation rate ε_B is shown in Fig. 6, *a*. Analysis of the calculation results has made it possible to establish that relative diameters of the protrusion and the wall varied almost linearly. After first reductions, relative diameter of the wall bore begins to increase more intensively than that of the protrusion. Under this condition, the wall length does not increase significantly. Intensive increase in the wall diameter after each expanding pass increases difference between diameters resulting in a growth of the forging taper. This is explained by different deformation rates in the protrusion and the wall.

Fig. 6, *b* presents data of deformation rates in the protrusion and the wall during each pass of the expanding process. Analysis of the obtained data has allowed us to establish that deformation rate in the wall is greater than that in the protrusion and rises more intensively after each circular pass of expanding. This causes an intensive increase in the wall bore diameter which is explained by different thicknesses of the protrusion and the wall because of the fact that the protrusion and the wall are deformed with the same reduction during each circular pass of expanding. The thicker wall has less relative deformation rate at the same reduction value.



a

b

Fig. 4. The forging after working: draft (*a*); strained state of the forging (*b*)

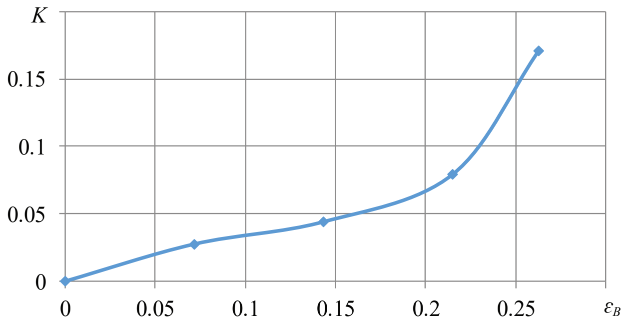


Fig. 5. Taper of the forging (K) depending on deformation rate of the protrusion section (ε_B)

Inside diameter of the wall section increases more intensively and the forging acquires a tapered shape during simultaneous expanding of the protrusion and the wall. Based on the results obtained, it can be concluded that when expanding stepped blanks with a stepped die, tapered shape of the forging is formed due to different deformation rates of the protrusion and the wall.

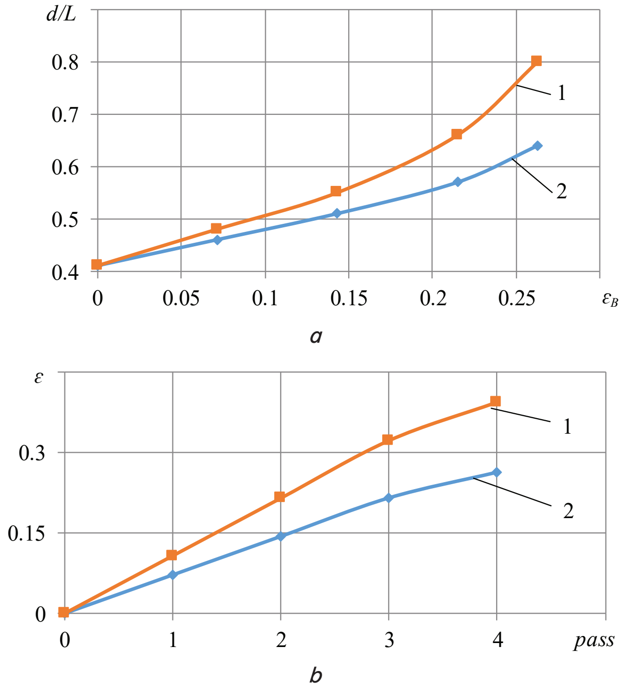


Fig. 6. Calculation results: relative bore diameter, d/L, depending on the protrusion deformation rate ε_B (*a*); deformation rate, ε, in the process of expanding (*b*); wall (1); protrusion (2)

6. Experimental modeling of the stepped blank expanding operation

6. 1. Shape change study with lead blanks

When expanding stepped blanks, uneven deformation of the wall and the protrusion occurs resulting in a taper formation. Dependences of the shape change during expanding operation with a stepped die have to be established by experimental studies. Fig. 7, *a* shows the shaped stepped blanks with a relative wall diameter D_y/d_{cp}=2.05. As a result of expanding, the samples had a tapered shape with a large wall section diameter.

Analysis of the results of relative deformation rates of the protrusion and the wall in the expanding process has allowed us to establish that deformation rate of metal in the wall becomes greater than that in the protrusion with each blank reduction pass (Fig. 7, *b*). It was established that a decrease in the relative diameter of the protrusion and, respectively, its wall thickness leads to an increase in the difference between relative deformation rates. This is explained by the fact that more intensive increase in diameter will occur in the thin wall zone at simultaneous reduction of the protrusion and the wall by an identical absolute value. This is because of the greater relative deformation of metal which contributes to increase in diameter of the forging wall.

Uneven change of relative diameters of the bores results in formation of the forging taper. Taper of the forging depends on basic parameters: diameter of the protrusion bore, $d_{n.b}$, and diameter of the wall bore, $d_{n.y}$. In this regard, it is advisable to study interaction of these two taper components during expanding.

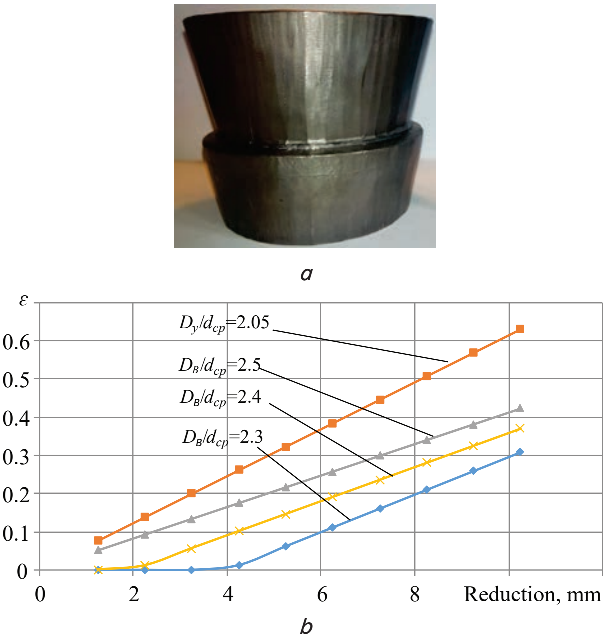


Fig. 7. Experiment results: lead blanks after expanding (*a*); dependence of relative deformation rates (ε) on reduction for blanks with different D_B/d_{cp} (*b*)

Analysis of the change of relative bore diameters of the protrusion and the wall sections in the process of expanding (Fig. 8) has shown that bore diameters of the wall section increase more intensively than those of protrusion section which confirms theoretical study results. With a decrease in relative protrusion diameters, D_B/d_{cp}, relative bore diameters $d_{n.B}/L_n$, of the protrusion decrease, the curve corresponding to D_B/d_{cp}=2.5 is higher and the curve corresponding to D_B/d_{cp}=2.3 is lower. On the other hand, with a decrease in relative diameters of the protrusion, D_B/d_{cp}, relative diameters of the wall bore, $d_{n.y}/L_n$ increase, the curve corresponding to D_B/d_{cp}=2.3 is higher and the curve corresponding to D_B/d_{cp}=2.5 is lower.

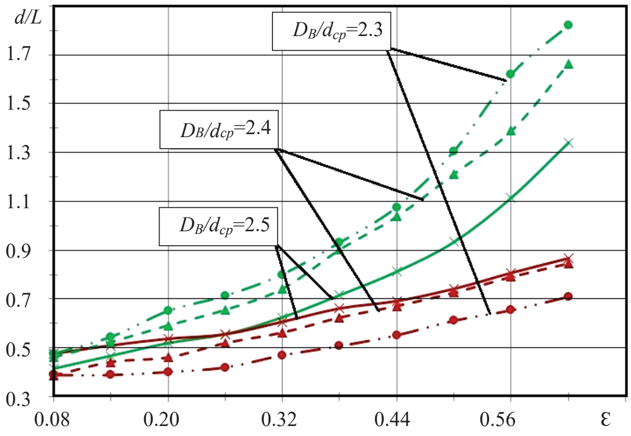


Fig. 8. Change of relative bore diameters, d_n/L_n, depending on the relative deformation rates in the wall, ε, for blanks with D_y/d_{cp}=2.05

As a result, for the studied scheme of expanding blanks with D_y/d_{cp}=2.05, difference between relative protrusion bore diameters, $d_{n.B}/L_n$, and relative wall bore diameters, $d_{n.y}/L_n$, constantly grows with a decrease in relative diameter D_B/d_{cp} which leads to taper formation.

Another pattern is characteristic for relative diameter of the blank protrusion D_B/d_{cp}=2.5. At the start of expanding, relative diameter of the protrusion bore is larger than that of the wall bore ($d_{n.B}/L_n > d_{n.y}/L_n$) which is accompanied by the protrusion deformation (the wall is not deformed at the start). When reaching relative protrusion deformation of 0.25, bore diameters in the protrusion and the wall are equalized ($d_{n.B}/L_n = d_{n.y}/L_n$) followed by an intensive growth of the wall bore diameter ($d_{n.B}/L_n < d_{n.y}/L_n$).

Special attention should be paid to expanding a sample with D_B/d_{cp}=2.5. A tapered shape with a large protrusion diameter was formed for it at the initial stage of expanding. The sample shape became cylindrical when ε_y=0.25 and the bore diameters were equal at both ends. Intersection of two curves in Fig. 8 corresponds to this condition for D_B/d_{cp}=2.5. As reduction increased, the wall deformation rate increased contributing to formation of maximum wall diameter. Taper was constantly growing for the other two samples.

Analysis of the results of taper formation in forgings depending on relative deformation rate of the wall has made it possible to state (Fig. 9) that for a relative diameter of the blank, D_y/d_{cp} equal to 2.05, increase in relative reduction in the wall section leads to the taper growth. Increase in taper is connected with an intensive increase in the wall bore $d_{n.y}$ during expanding operation. Reduction of taper in blanks with relative protrusion diameters of 2.5 at reduction rate $\varepsilon < 0.26$ is connected with forging in the first pass of the ring protrusion expanding operation. The wall is not deformed in this case. So, the protrusion diameter begins to increase and the wall diameter does not change. A tapered ring with protrusion diameter (D_B/d_{cp}=2.5) is formed. Further deformation of the wall and the protrusion results in the taper decrease to zero after reduction rate of $\varepsilon = 0.26$, which indicates equality of diameters of the wall and the protrusion sections ($d_{n.B}=d_{n.y}$). Growth of taper for a blank with relative protrusion diameter of 2.0 is connected with more intensive increase in the wall bore diameter which is explained by a large metal flow in tangential direction when thin wall is reduced.

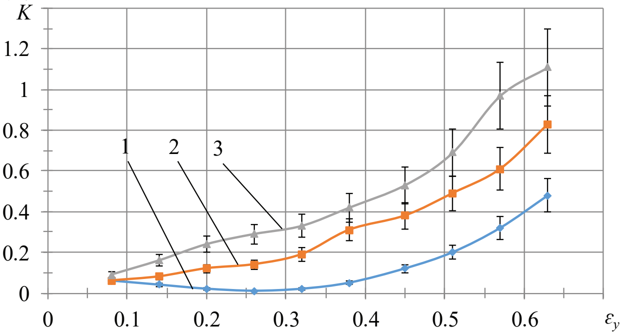


Fig. 9. Change of taper (K) depending on relative wall deformation (ε_y) for blanks with D_y/d_{cp}=2.05 (1); D_B/d_{cp}=2.40 (2); D_B/d_{cp}=2.30 (3)

The change of ratio of the protrusion and the wall bore diameters during the expanding process which allows one to establish qualitative and quantitative change of diameters at the blank ends at a constant length of the blank gives an important result. Analyzing the change of ratio of the forging bore diameters in the protrusion and the wall, $d_{n.B}/d_{n.y}$ depending on deformation rate, ε_y, (Fig. 10) for the relative diameter of the wall, D_y/d_{cp}=2.05, it can be noticed that as deformation rate ε_y increases, ratio of the forging bore diameters decreases. The point on curve 1 marked by a circle corresponds to absence of taper. These diameters at the marked point coincide ($d_{n.B}=d_{n.y}$) and with further deformation, diameter of the wall section bore increases more intensively than that of the protrusion section and the ratio of the end diameters $d_{n.B}/d_{n.y}$ of the forging becomes less than 1.0 ($d_{n.B} < d_{n.y}$).

Curves 2 and 3 lay not upper than value of 1.0 which corresponds to the wall section deformation at the start of expanding. Their gradual lowering occurs because of the fact that the wall diameter increases more intensively due to the greater accumulation of deformations. Moreover, the obtained regularities have practically linear dependence.

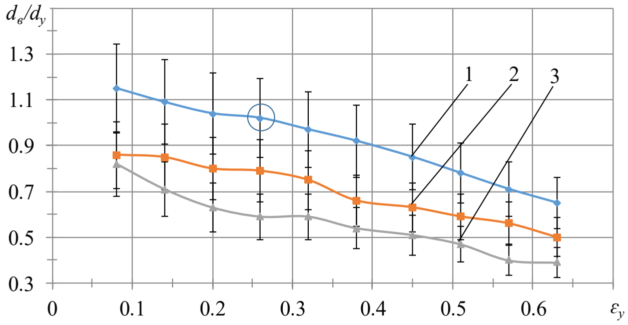
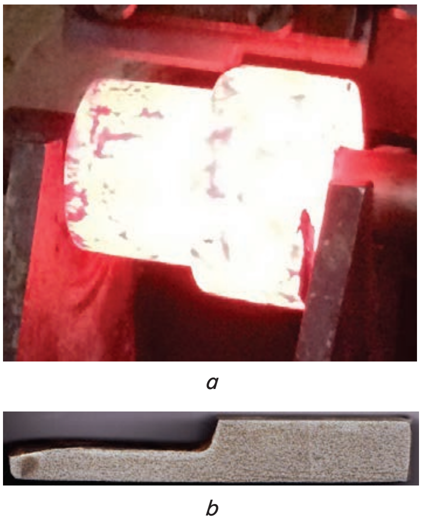


Fig. 10. Change of the ratio of bore diameters depending on deformation rate in the protrusion section for the blanks with D_y/d_{cp}=2.05: for D_B/d_{cp}=2.5 (1); for D_B/d_{cp}=2.4 (2); for D_B/d_{cp}=2.3 (3)

6. 2. Expanding study with steel blanks

The new technology of forging stepped tapered rings (Fig. 11, *a*) assumed blank heating and drawing on a mandrel, heating and expanding until specified forging dimensions are achieved. Specimens were cut along axis of annular forgings for metallographic studies (Fig. 11, *b*).


a

b

Fig. 11. Experimental study: the process of expanding steel blanks in a hot state (*a*); the forging macrostructure in a cross-section (*b*)

Analysis of the obtained results has made it possible to establish that the new forging technology ensures compression of the metal fibers in the wall more densely than in the protrusion (Fig. 11, *b*). The fiber direction repeats the stepped forging profile which excludes cutting of the metal structure as is the case with machining according to the conventional technology.

7. Discussion of the results obtained in expanding tapered stepped rings

According to the study results, SSS of the blank and regularities of change of the ring dimensions during the expanding process have been established. Analysis of the obtained results has allowed us to establish effective conditions for the process of expanding tapered rings and its advantages before the existing method of deformation:

– the use of a stepped blank for expanding has enabled manufacture of tapered rings which was impossible earlier. This is explained by the fact that increase in the wall diameter occurs more intensively which imparts tapered shape to the blank;

– the use of a stepped die makes it possible to manufacture rings with a stepped profile which eliminates use of excess machining allowances and increases metal utilization by 7 %;

– expanding with the help of a stepped die has enabled manufacture of forgings repeating contour of the target parts which has eliminated machining operation in the wall formation and made it possible to reduce machining time as well as improve metal quality in the zone of the protrusion transition to the wall by eliminating cutting of the metal structure fibers.

Constraints of the developed method of expanding tapered stepped blanks include the following:

– the proposed expanding method can be used in the manufacture of tapered rings only with a stepped profile;

– the process of the hollow blank manipulation on the mandrel becomes more complicated at significant values of the ring taper.

The recommendations on geometrical parameters of the blank, tools and expanding conditions worked out in this study are important scientific and technical results that can be used in the theory and practice of manufacture of large-size hollow forgings.

Practical aspect of using the study results consists in improvement of the technological process of expanding tapered forgings with a stepped profile.

Previously, methods of obtaining cylindrical rings were studied. The current study considers the method of making tapered rings by forging.

However, results of the study of applicability of the proposed method to the manufacture of tapered rings with expansion towards the blank protrusion were not presented. Therefore, further studies should be conducted to determine effect of the stepped blank geometry and the tool shape on the possibility of expanding the forging protrusion diameter.

8. Conclusions

1. Special procedures for studying ways of expanding stepped tapered rings have been developed. Theoretical studies of shape change and SSS in tapered blanks with a stepped profile have been conducted. It was established that when the stepped blank is shaped, its wall increases in diameter more intensively than that of the protrusion due to which the forging acquires a tapered shape. This is explained by different rates of deformation applied to the protrusion and the wall and the more intensive growth of deformation rate in the wall than in the protrusion. The difference in deformation rates arises from the difference in thickness of the wall and the protrusion. Taper is 0.17 at $\varepsilon_B=0.25$.

2. Based on the experimental studies of expanding tapered rings, it was established that an increase in relative wall diameter, D_y/d_{cp}, leads to an increase in the rate of deformation of the wall and, accordingly, to an increase in diameter of the resulting wall section. As a result, difference between the protrusion and the wall affects variation of the taper during expanding. Expanding of blanks with relative diameter $D_y/d_{cp}=2.05$ and increasing rate of deformation (ε) brings about increase in the relative diameter of the wall, $d_{n.y}/L_n$ and decrease in the ratio of diameters of the forging wall and protrusion, $d_{n.B}/d_{n.y}$. Moreover, the taper growth occurs as the relative diameter of the blank protrusion, D_B/d_{cp} decreases.

3. Macrostructure examination of the forgings obtained by the new technology has shown that during expanding of a stepped blank with the help of a stepped die, metal fibers repeat the part contour which excludes their cutting during machining.

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