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DESIGNING OPTIMAL GEOMETRY OF THE RADIUS DIE FOR BROACHING CASES

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The object of this study is the technological process of broaching cartridge cases through a radius die on a mandrel. The work is aimed at solving the actual scientific and technical task of improving the technological process of broaching on a mandrel through a die in the manufacture of cartridge-case type forgings, which provides an increase in the stability of broaching dies. The finite element method (FEM) was used to simulate the processes of broaching cartridge cases through the die. As a result, a rational geometry of the radius die has been established. Recommendations for designing new die structures have been devised, which involve determining the rational radius of rounding of the working part of the die. The established recommendations have been verified by experimental studies. The broaching of cartridge cases through a die with a working radius surface should be carried out at relative radius R/d=3.0. In this case, stress intensity decreased by 7...17 %, average compressive stresses decreased by 8...15 %, and normal pressure decreased by 10...15 % compared to smaller rounding radii. The resulting force on the working surface of the die decreased by 40...55 %, and the radial component of this force decreased by 50 %. It was found that the working surface of the die is heated to a temperature of 750...850 °C, but the rounding radius R/d=3.0 provides a reduction in the volume of this zone by 1.5...1.9 times. The resulting relative rounding radius of the die was tested under industrial conditions, which confirmed that the broaching force for this radius is lower by 15...20 %, and the stability of such a die increased by 20 %. It is recommended to use radius dies for broaching high cartridge cases. The results could also be applied at enterprises during the production of dual-purpose parts

Keywords: cartridge case, broaching, die, rounding radius, wear, mandrel, stability, broach force, hollow workpiece, FEM

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1. Introduction

Among forgings for critical purposes, high cases occupy a special place. Such parts as cylinders, shells, bodies of hydraulic and pneumatic cylinders, etc. are made of them. This is, as a rule, serial production, which amounts to hundreds of thousands of parts per year. The weak points of such production are significant allowances for mechanical processing, low durability of broaching dies, and the use of specialized high-speed hydraulic presses with a long stroke. The main shaping operation for these forgings is broaching a thick-walled cup through a die using an internal mandrel. Dies include a conical or radius working part. Dies with a conical working surface are well known. Dies with a working surface made along a radius curve have been little studied. Such die geometry should increase the durability of broaching dies. Therefore, improving the broaching process by using specially shaped dies is an urgent problem.

2. Literature review and problem statement

There is little information in current literature regarding the operation of broaching on a mandrel through dies but the problem of die and stamp durability under hot strain remains a pressing issue [1, 2].

In [3], an experiment was conducted on forming a projectile body on a hydraulic press. The formed projectile has the desired microstructure and good combined mechanical properties with a saving of 30 % of metal. However, the issues of increasing the durability of broaching dies, which are the most loaded tool, are not considered. The likely reason is ruling out the option of changing the die working geometry.

The purpose of study [4] was to provide a new point of view on the types of die failure, such as wear (abrasive and adhesive), plastic deformation, fatigue (thermal and mechanical). These problems arise due to high thermal effects, mechanical stress, and corrosion during hot forging, as well as the influence of frictional forces that occur during radial extrusion [5]. In this case, an increase in the resource of dies is considered only through the use of special alloys. This is due to the elimination of the influence of reactive friction forces that could relieve the deformation process.

In [6], the application of a die insert coating for hot hammer forging is investigated under actual industrial conditions. An optimized die insert shape design to reduce the critical load that causes premature failure, combined with an improved plasma nitriding process, is proposed to extend the service life of the die insert. However, the proposed recommendations apply to hammer dies, which are less loaded and are not suitable for broaching dies.

In [7], a finite element model was built to study the thermomechanical fatigue behavior of hot-working steel. Experimental results on the fatigue properties of 9Cr steel were used. Then, thermomechanical fatigue was simulated for a hot forging die with prediction of the initiation and growth of a fatigue crack. However, the model built did not take into account the abrasive and adhesive wear of the working surface of the die.

In [8], a composite based on $TiB_2{\cdot}TiAl_3$/2024Al was subjected to multi-directional forging, and the effect of temperature and the number of forging passes on the microstructure and mechanical properties of the composite was studied. The improvement in strength caused by such treatment for the studied composite was quantitatively analyzed using hardening mechanism models. However, it was found in the work that the calculated results showed that the load and thermal expansion lead to a decrease in strength due to an increase in grain size. Therefore, the problem was not fully solved.

The authors of work [9] developed an optimization algorithm to obtain the optimal parameter, which takes into account the temperature of the workpiece and the rate of deformation during forging process. In this case, the work notes that the experimental results show that the algorithm did not always exclude unstable areas. Therefore, the results should be further verified.

Paper [10] considers the possibilities of using various methods to increase the service life of pressing tools. It also reports the use of control and measurement systems that allow full control over the stamping process, and the use of innovative solutions that allow for an effective increase in the service life of pressing equipment [11]. However, the papers show that the use of a number of methods based on automated means cannot always solve the problems associated with the short service life of the tool. Therefore, these developments should be clarified and expanded towards increasing the service life of dies.

Study [12] is a review showing the possibilities of applying modern measurement methods in the stamping industry using various measuring tools, devices, and machines used in shop metrology. The paper points out various aspects of measurement methods, emphasizing their importance in the context of safety (resulting forging products) and significant measurement problems because of extreme conditions in industrial hot forging processes (high cyclic mechanical loads and temperatures). However, the reported applications of numerical simulation results for determining physical quantities are difficult, and sometimes impossible, to verify under industrial conditions (temperature distribution, stress, deformation, etc.). That requires a change in the approach to increasing the durability of the deforming tooling.

In study [13], the temperature field, stress field, and wear state of the die during hot stamping were predicted and estimated using a finite element modeling (FEM) analysis. The experimental results confirmed that wear mainly occurred in the areas of the bridge, lug, and grooves of the hot stamping dies. Based on the analysis and experimental results, the wear of large dies was restored using bimetallic surfacing technology. This technology for surfacing bimetallic layers reduced the cost of production but did not contribute to increasing the durability of dies, rather it was aimed at their repair after wear.

The studies reported in [14, 15] showed that the die at the finishing stage broke prematurely at a small fillet radius because of mechanical fatigue. To eliminate this problem, the insert was redesigned for a hot fit in a shrink ring. The FEM result was confirmed experimentally in a real process. However, the work addressed the problem of the resistance of stamping lugs to stamping forces; the wear of the die groove was not studied in the work. Therefore, this work does not solve the problem of the resistance of broaching dies.

Studies [16, 17] are aimed at increasing the fatigue strength of cold stamping dies used in the mass production of automotive parts. Stresses in the die were estimated using FEM, which made it possible to determine the location of the crack initiation and the direction of its propagation. At the same time, the procedure described in the work could only serve as valuable recommendations for the design of cold-working dies that are less susceptible to fatigue failure and adhesive wear as in hot stamping.

Paper [18] presents a critical review of failures and treatment methods used to improve the surface integrity of stamping tools used in the hot forging process. It is shown that there is no comprehensive review of failures and methods to solve this problem in the general case to predict the failure of the hot stamping tool.

Work [19] investigates the chemical properties of the materials of dies used in hot stamping. Depending on the chemical composition and the heat treatment process, which is used for hot-deformed tool steel based on tungsten and chromium to achieve a given microstructure, the hardness of the materials was established. The work makes it possible to select an alloy with the required content of alloying elements of the die, taking into account the specified hardness. The data on the microstructure and hardness of the materials under study established in the work do not take into account the effect of strong heating of the die when broaching high cases. But this heating changes the microstructure and hardness of the working surface of the die. Therefore, the issue of the durability of dies is not resolved in the work.

In order to increase the service life of dies, a large number of dies used in real production were studied in detail [20]. The most worn area of the dies has a high surface roughness, which forms a corresponding pattern on the elements of the die groove. However, the work does not propose effective ways to increase the durability of broaching dies.

In [21], the factors considered were limited by process parameters that could be directly changed in a real industrial process. A two-stage deformation cycle was taken into account when assessing the stress distribution on dies [22] and when assessing the die wear. However, the work noted that in the presence of high process instability, only the ability to effectively control most of the causes of die wear was demonstrated. But a decrease in the rate of die wear is not presented in the work.

The DEFORM FEM software was used to analyze the durability of hot stamping dies [23], and the Archard wear model was applied to predict the wear surface of the die [24]. For a deep study of stamping slopes and fillet radii, the commercially available ABAQUS software determined the distribution of deformation rate fields on the die surface. Also, the effect of temperature on the wear coefficient and contact pressure for each die point at each time step was taken into account to determine the wear depth. However, temperature and pressure are not enough for a comprehensive assessment of die durability; average stresses should be established to determine the sign and magnitude of principal stresses. Analysis of the deformation process force mode should also be carried out.

Work [25] considers the durability of punches used in the process of industrial precision stamping in the manufacture of valve forgings for truck engines. Tool wear was analyzed and represented by the destruction of the material on the working surface of the punches based on 3D scanning and measurement of the die cavity volume on periodically measured forgings.

Based on the above review, it was found that several different mechanisms dominate die and deforming tool destruction (coating chips and adhesive wear). The best results were obtained using special titanium nitride coatings. At the same time, many of the considered works noted that the results were not verified by tests under industrial conditions. Therefore, the reported results are subject to additional study.

3. The aim and objectives of the study

The aim of our work is to design a new geometry of a radius die for broaching high cases based on a quantitative assessment of the stressed, force, and thermal state, which will make it possible to increase their durability in serial production.

To achieve the goal, the following tasks were set:

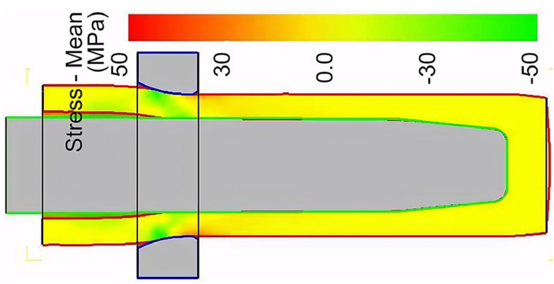
– to determine the stressed state on the working surface of a radius die with different rounding radii (stress intensity, average compressive stresses, normal pressures, resulting force, its radial component, thermal state, as well as force parameters of the process);

– to test the resulting new geometry of the die experimentally.

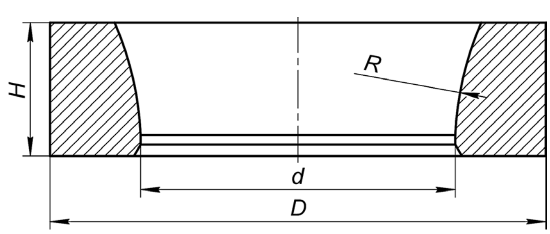
4. The study materials and methods

The object of our study is the technological process of broaching thick-walled cups through a radius die on a mandrel (Fig. 1, *a*).

The hypothesis of the study assumes that broaching cups through a radius die (Fig. 1, *b*) could increase the durability of the die by changing the stressed-strained state in the workpiece metal, which would reduce the costs of producing broaching dies.



a



b

Fig. 1. Modeling of a new broaching process: *a* — calculation scheme; *b* — schematic of the radius die

The main assumption of the study is the constancy of the speed of pushing a hollow workpiece through the die.

At the first stage, to assess the loads on the tool, the effect of the stress state on the working surface of the die was established, then the force and pressure of deformation, as well as the thermal state of the die during the broaching process. Based on the results of this study, a rational geometry for the radius working surface was determined, which would reduce the loads on the die.

The study of the broaching process was carried out at various relative radii of rounding of the working part of the die (R/d) in the range of 0.75; 1.0; and 3.0. The thickness of the cup wall was constant for all cases, the diameter of the die hole was also constant to ensure the same degree of deformation (broaching ratio). The stress, force, and thermal state during hot broaching through the die (Fig. 1) was determined using FEM. A special research methodology was devised to model the broaching process. Steel C-60 was designated as the material under study.

The initial parameters and boundary conditions for modeling hot broaching through a die were as follows: the Young's modulus for this steel was 2 10^5 MPa; the Poisson's ratio was 0.32, the tool temperature was 300 °C, and the Siebel friction coefficient was 0.3. The number of finite elements specified in the workpiece was 40,000 and in the die 32,000. The workpiece material model was plastic, and the die material model was elastic. The workpiece heating temperature was 1100 °C, and the mandrel movement speed was 60 mm/s.

5. Results of investigating the process of broaching a workpiece through a radius die

5. 1. Determining the stressed state on the working surface of a radius die with different rounding radii

The durability of the die could be estimated by the stress state in the die. A simple indicator of the stressed state is the intensity of stresses on the working surface (Fig. 2). Analysis of the results allowed us to establish the following. Small rounding radii of the lead-in part of the die (R/d=0.75) leads to the localization of maximum stresses (shown in blue in Fig. 2) on the curvilinear part (Fig. 2, *a*). For such geometry, the stress level is 523 MPa. Such localization of stresses will contribute to increased wear in this zone.

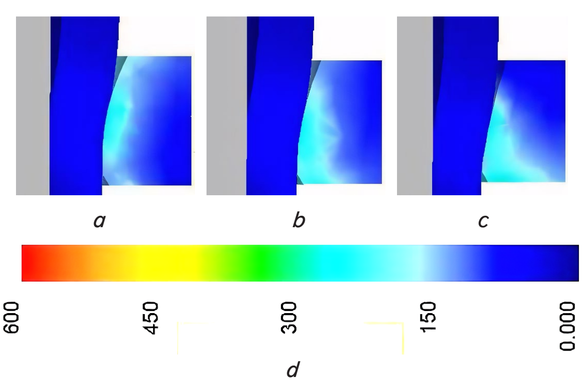


Fig. 2. Stress intensity in the workpiece and tool during broaching: *a* — R/d=0.75; *b* — R/d=1.0; *c* — R/d=3.0; *d* — stress intensity distribution scale

Increasing the die rounding radius to R/d=1.0 changes the shape and dimensions of the stress intensity field (Fig. 2, *b*).

The stress field drops, and the die calibrating belt begins to be loaded. The stress level increases to 578 MPa. Consequently, such a rounding radius will contribute to increased die wear. Increasing the die rounding radius to R/d=3.0 changes the shape of the stress field, which continues to drop downwards to the die support surface (Fig. 2, *c*). However, the stress intensity level decreases and its maximum is 489 MPa. It is difficult to draw a final conclusion about the effect of stress intensity fields on the wear of the die working surface. To this end, it is necessary to determine the sign of the stresses on the contact surface. The wear of dies is affected by contact stresses and pressures on the tool. Regarding stresses, their sign should be taken into account: whether they are compressive or tensile. Compressive stresses on the surface will contribute to the wear of the die working surface. Therefore, at the second stage it is necessary to determine what stresses act from the workpiece on the working surface of the die, their level, and the sign of these stresses. Compressive stresses have a minus sign. The sign of the stresses could be determined by the distribution of average stresses. They show the level and sign of the prevailing stresses. The distribution of average stresses in the workpiece and tool is shown in Fig. 3.

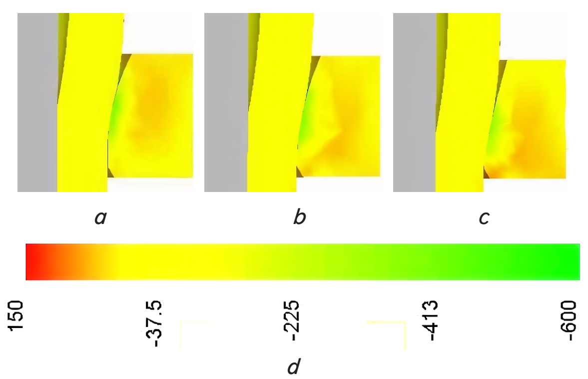


Fig. 3. Distribution of average stresses in the workpiece and tool during broaching: *a* – R/d=0.75; *b* – R/d=1.0; *c* – R/d=3.0; *d* – scale of distribution of average stresses

Analysis of compressive stress fields (shown in green in Fig. 3) reveals the following. The sizes of the zone and the shape of the field of maximum compressive stresses for the studied schemes are different. For a small radius of the lead-in part (R/d=0.75), the field of maximum compressive stresses is located above the calibrating belt of the die (Fig. 3, *a*), their value reaches – 648 MPa. An insignificant gap is formed between the outer surface of the workpiece and the calibrating belt of the die. This explains the unloading of the calibrating belt, and accordingly leads to intensive loading and, consequently, to increased wear of the working surface of the die.

Increasing the rounding radius to R/d=1.0 (Fig. 3, *b*) of the lead-in part of the broaching die leads to an increase in the level of compressive stresses (–689 MPa). In this case, the height of the compressive stress field is greater than for the previous scheme. Further increase of the rounding radius of the lead-in part of the die to R/d=3.0 (Fig. 3, *c*) qualitatively and quantitatively changes the distribution of average stresses on the working surface. Namely, the area of the stress field decreases, and the level of compressive stresses also decreases (–601 MPa). This allows us to conclude that such radii of rounding of the die are more preferable and could increase the durability of the die.

An alternative indicator of loads on the working surface of the die is also the resulting force of action from the workpiece metal during broaching (Fig. 4). The zone of force application coincides with the areas of occurrence of maximum stresses (see the figures above). Analysis of the results allowed us to conclude that with an increase in the rounding radius, the resulting force on the working surface of the die decreases. Thus, for a small radius R/d=0.75, the maximum forces of action are 14000...18000 N; for a radius R/d=1.0 they are 12000...16000 N; for radius R/d=3.0 they are 9000...13000 N. The area of application of forces corresponds to the area of contact of the workpiece with the die and is approximately the same for the considered schemes.

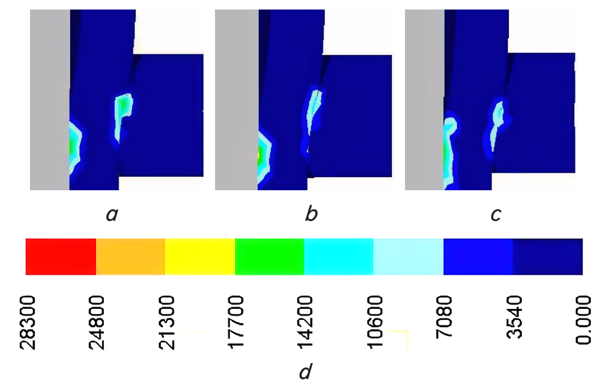


Fig. 4. Distribution of the resulting force of the workpiece on the tool during broaching process: *a* – R/d=0.75; *b* – R/d=1.0; *c* – R/d=3.0; *d* – distribution scale of the resulting force

The distribution of the radial components of the forces acting on the die is shown in Fig. 5. The maximum force acting on the working surface of the die is shown in yellow in Fig. 5. Analysis of the results allowed us to conclude that with an increase in the rounding radius, the radial force acting on the working surface of the die decreases. Namely, for radius R/d=0.75, the maximum radial forces are 6000...12000 N; for radius R/d=1.0, they are 5000...10000 N; for radius R/d=3.0, they are 4000...8000 N.

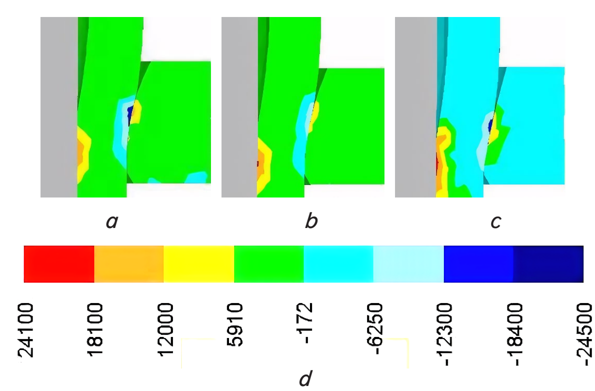


Fig. 5. Radial component of the workpiece impact force on the tool during broaching: *a* – R/d=0.75; *b* – R/d=1.0; *c* – R/d=3.0; *d* – impact force distribution scale

In order to move away from the absolute dimensions of the dies and to switch from absolute values of forces to relative ones, the fields of distribution of normal pressures of the workpiece metal on the die were considered (Fig. 6).

Analysis of the results allowed us to conclude that the minimum normal pressure occurs at radius R/d=3.0 and is 1240 MPa (Fig. 6, *c*). In other cases, these pressures are 10...15 % higher.

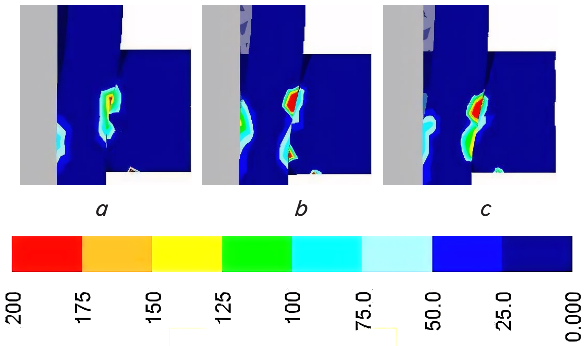


Fig. 6. Distribution of normal pressures of the workpiece on the tool during broaching: *a* – R/d=0.75; *b* – R/d=1.0; *c* – R/d=3.0; *d* – scale of distribution of normal pressures

Temperature has an important effect on the durability of the die. Analysis of the temperature distribution results revealed that the working surface of the die is heated minimally for large rounding radii (Fig. 7, *c*). In this case, the heating zone is also smaller. This is explained by the smaller contact area of the workpiece metal with the die due to the shorter arc length of the die working zone. The maximum temperature of die heating is 750...850 °C, but the size of the zone (volume) of such heating is different. So, for large rounding radii, the volume of heating to these temperatures is almost 1.5...1.9 times smaller.

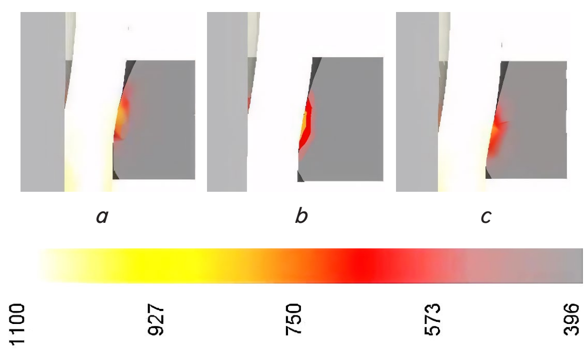


Fig. 7. Temperature distribution in the workpiece and tool during broaching: *a* – R/d=0.75; *b* – R/d=1.0; *c* – R/d=3.0; *d* – temperature distribution scale

An indirect indicator of increasing the die resistance is a decrease in the deformation force during the broaching process. For this purpose, a plot (Fig. 8) of the force change during the deformation process was constructed for three different die geometries (R/d=0.75; R/d=1.0; R/d=3.0). Analysis of the results allowed us to establish that the minimum broaching force at the main stage of deformation (steady-state stage) was minimal for the rounding radius R/d=3.0 and amounted to approximately 330 MN.

The minimum deformation force for the relative radius of the die rounding R/d=3.0 is explained by the low pressures and stresses that act on the die for this geometry (Fig. 3–7).

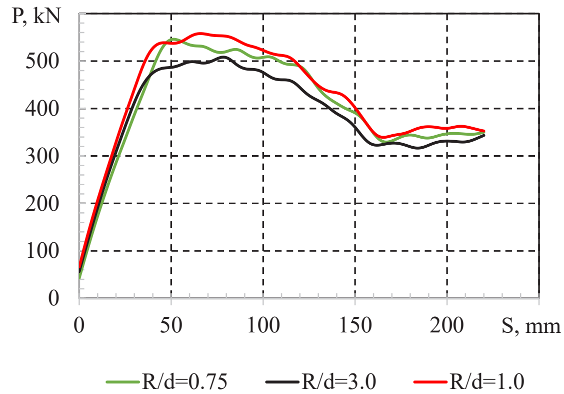


Fig. 8. Deformation force during broaching for different die rounding radii (R/d=0.75; R/d=1.0; R/d=3.0)

5. 2. Experimental verification of hot broaching resistance for dies of new geometry

The results of our theoretical study showed that the minimum loads on the die occur when broaching through a die with relative radius R/d=3.0. For this geometry, a die was designed and manufactured from 4X5MFS steel. The die opening diameter (*d*) was 164 mm, the rounding radius of the die working surface (*R*) was 492 mm. The die was mounted on a hydraulic press with a large stroke and a force of 600 MN. The broaching process was carried out in a hot state with a temperature of approximately 1000 °C, using oil-graphite lubricant, which was supplied directly to the working area of the die. The die and mandrel were cooled with running water. The peak broaching force was 480 MN, the main working force was about 300 MN. After hot broaching of 2200 forgings through this die, the die acquired noticeable traces of wear (Fig. 9). Intensive wear emerged in the place of occurrence of maximum stresses and pressures from the workpiece on the working surface of the die. The calibrating belt has shallow scratches, which were caused by the effect of scale, which remained on the surface of the workpiece. The working surface of the die has strong local wear, which could be corrected by surfacing and grinding. After broaching, the forging was cooled in air.

Fig. 9. Die after broaching for rounding radius R/d=3.0

Thus, our experimental results coincide and confirm the theoretical study based on FEM. It was found that large radii of rounding of the working surface reduce the loads on the working surface of the die and contribute to an increase in the durability of the die as a whole. After changing the internal geometry of the die, the durability increased by 20 %.

6. Discussion of results of investigating the possibility of using radius broaching dies for broaching high cartridge cases

Based on the results of our theoretical study, it was found that small radii of rounding of the working surface of the die lead to the occurrence of high stresses and pressures on the working surface from the side of the hot billet (Fig. 2, 3, 6). This could be explained by the fact that with small radii of rounding, the formed arc has a large deflection arrow, which increases the resistance to the flow of metal into the die hole (Fig. 8). This leads to an increase in energy costs (the deformation force increases), which accordingly act through contact stresses and pressures on the working surface of the die (Fig. 8). In this case, relative radii of rounding $R/d>3.0$ should be used.

The stress intensity did not fully resolve the stressed state on the working surface of the die (Fig. 2); this could be explained by the fact that this parameter is an average integrated value. Increasing the rounding radius allowed us to reduce the intensity of stresses by 7...17 %, and the study of the fields of average stresses allowed us to determine the compressive stresses and their level (Fig. 2, 3). This is explained by the fact that with small radii of rounding of the working surface of the die, the contact spot of the metal of the workpiece with the die has a smaller area, however, significant compressive stresses are localized in this place, and they are located noticeably above the calibrating belt of the die (Fig. 3). This relieves the belt from intense stresses; moreover, in this case, broaching occurs with the formation of a gap in this zone.

The decomposition of stresses into forces acting on the working surface of the die made it possible to establish that the distribution of stress fields coincides with the fields of occurrence of maximum forces (Fig. 4). The magnitude of these forces decreases with an increase in the rounding radius R. With rounding radius $R/d=3.0$, the resulting force decreases by 40...55 %. This is explained by the fact that the selected radial component displays a decrease in force (Fig. 8) with an increase in the rounding radius, as well as the approach of the source of maximum forces to the calibrating belt (Fig. 3). An increase in the rounding radius made it possible to reduce the radial component of the force to 50 % (Fig. 5). The same applies to normal pressures, which made it possible to take into account the area of action of contact forces (Fig. 6). An increase in the rounding radius makes it possible to reduce normal pressures by 10...15 %. These results are explained by the fact that with large rounding radii, the arc length decreases, and accordingly the area of action of friction forces decreases (Fig. 5). For a comprehensive assessment of the die durability, the temperature of the loaded zone of the die should be taken into account. The heating zone and the zone of localization of forces and stresses coincide. This would lead to the fact that in this zone there could be maximum wear of the die. The maximum heating temperature of the loaded part of the die is about 750...850 °C (Fig. 7) and exceeds the heat resistance of the die steel 4X5MFS, this could lead to a decrease in the durability of the die. However, for large rounding radii, the volume of this heated zone will be 1.5...1.9 times smaller. This is explained by a smaller contact area and, accordingly, a smaller area of heat absorption by the die from the workpiece (Fig. 7).

The above results correlate with the data on the broaching force through different dies. Thus, for relative die rounding radius $R/d=3.0$, the broaching force will be lower by 10...15 % than for a smaller rounding radius. Experimental studies of the newly geometry confirm the results of FEM modeling. The location of the wear zone of the die coincides with the zones loaded with contact stresses and pressures. The broaching force was reduced by 15...20 %, and the durability of the die increased by 20 %. This is explained by a decrease in friction forces when broaching with large radii of rounding of the die (Fig. 8).

Unlike studies [5], which considered the effect of reactive friction forces on the broaching force in a conical die, there is a decrease in the broaching force in a radius die with a large radius of the working surface ($R/d=3.0$). This makes it possible to reduce contact pressures and stresses on the die, and accordingly reduce its wear. The task of devising a new geometry of a radius die for broaching high cartridge cases based on a quantitative assessment of the stress, force, and thermal state has been solved, which made it possible to increase their durability in serial production.

The limitations of our work are that relative rounding radii (R/d) greater than 3.0 have not been studied. This study has no shortcomings because the designated process has been studied comprehensively and in an integrated fashion.

Broaching a blank through radius dies is a new technique. To fully answer the question about the effectiveness of using these dies, additional studies should be conducted, which will be aimed at studying the effect of even larger rounding radii of broaching dies. Such studies could be the subject of further research by specialists in this field.

7. Conclusions

1. Based on the results of our theoretical and experimental studies, a rational rounding radius of the die, $R/d=3.0$, has been established, which enables the following:

– the stress intensity decreased by 7...17 %, average compressive stresses decreased by 8...15 %, and normal pressures decreased by 10...15 % compared to smaller rounding radii;

– the resulting force on the working surface of the die decreased by 40...55 %, and the radial component of this force by up to 50 %;

– the working surface of dies with different radii is heated to the same temperature (750...850 °C), but the rounding radius $R/d=3.0$ enables a decrease in the volume of this heated zone by 1.5...1.9 times.

2. It has been experimentally established that the broaching force for this rounding radius decreased by 15...20 %, and the durability of the broaching die increased by 20 %.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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