

INVESTIGATION OF THE STRESS-STRAIN STATE OF BALLS UNDER DEFORMATION IN A CLOSED DIE

Received – Primljeno: 2020-01-27

Accepted – Prihvaćeno: 2020-06-10

Preliminary Note – Prethodno priopćenje

The paper presents the results of the study of the production process of balls in a special closed die, which performs a full compression due to the alternate insertion of rams. The possibility of implementing the proposed method is proved experimentally, and the presence of high compressive stresses in the deformation center is shown using the method of sliding lines and mathematical computer modeling. Due to the alternate insertion of rams, the process of plastic deformation is intensified, which makes it possible to obtain high-quality balls. The maximum average stress in the deformation center obtained by the theoretical calculation method of sliding lines is – 436,94 MPa, and the values obtained by mathematical computer modeling is – 500 MPa. Metallographic analysis showed that the grain diameter of the obtained ball samples in the central part, compared to the initial samples, was crushed 3 times (up to 5 μm).

Keywords: high strength ball, forging, severe plastic deformation, stress-strain state, closed die, modelling

INTRODUCTION

It is known that metal balls work in very difficult conditions: shock and dynamic, under static loads and increased wear. This is especially true for the grinding balls of metallurgical mills, the cost of replacing which in some cases is equal to the cost of electricity.

The main requirements for grinding ball are reduce the wear rate and increase the grinding capacity [1, 2]. To meet these requirements, the first priority is increase strength characteristics of the balls. Many world manufacturers of solve this problem by using chromium and stainless steel, nickel-based alloys (hastelloy, inconel, monel), cobalt (stellite), wear resistant alloys (tungsten carbide, tool steels), bronze, brass and even rare-earth materials, which, in comparison with ordinary carbon steels, are characterized by increased strength characteristics, but are expensive, and, therefore, their use is largely economically inexpedient.

Therefore, the research and development of processing methods that would provide enhanced strength, plastic and other performance properties of preferably inexpensive ordinary steel grades (for example, carbon instead of the above) is an urgent problem at this stage of the development of metallurgy and mechanical engineering.

Balls are currently obtained by hot die forming (forging) [3], casting [4], and cross-screw rolling [5] in different variations. Also, methods of intensive plastic

deformation [6 -8], which, using various schemes and combinations of stress-strain conditions, make it possible to obtain materials with ultrafine-grained and nanostructure at relatively low cost, have recently become very popular. These methods of producing balls have their advantages and disadvantages.

These methods are well studied, but the point of view of the stress-strain state, which generally affects the quality of the balls, has not been studied much.

The authors of this work tried to combine the hot forging process with severe plastic deformation (SPD) in one combined process, which would combine the optimal stress-strain conditions for volumetric study of the material structure.

EXPERIMENTAL PART

In this paper, it propose a scheme for producing balls, which significantly intensifies the process of plastic deformation due to comprehensive compression of the balls by alternately pressing rams in a closed die enclosed in a container with clamps (Figure 1).

The process of processing balls is as follows: the initial cylindrical workpiece (billet), the volume of which is equal to the volume of the cavity of the closed die, is installed on the lower half-die 4, where there are orifices for inserting lateral rams 5. Next, the upper half-die 2 together with the ram 3 pull the workpiece until the die cavity is completely filled using the upper ring 6 and the lower ring 7. After filling the cavity of the die, the closed cavity is fixed with screws 9, and the alternate insert of the central 3 and lateral 5 rams begins. In this case, the stamping equipment is installed on the

M. Abishkenov (e-mail: maks91.kz@inbox.ru), Zh. Ashkeyev, G. Akhmetova, I. Volokitina, Karaganda state industrial university, Temirtau, Kazakhstan; S. Mashekov, Satbayev University, Almaty, Kazakhstan

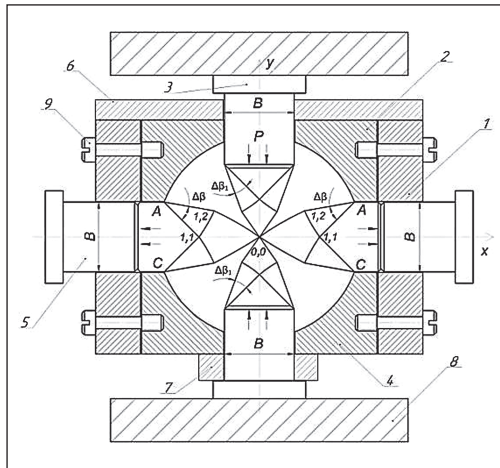


Figure 1 Closed die design for comprehensive intensive processing of balls and the field of slip lines when inserting the central rams and displacing the lateral rams

bottom plate of the press 8. Alternating deformation is carried out by the tilting of the die tooling after each cycle by 90° . A distinctive feature of the proposed method of obtaining balls from existing ones is that it provides comprehensive compression by rams, which provides an increase in strength, plastic and other properties due to alternate indentation in several cycles.

To test the operability and effectiveness of the proposed method, laboratory experiments were carried out using the corresponding experimental samples of plasticine and structural carbon steel AISI 1060 on a single-column semi-industrial hydraulic press.

RESULTS AND DISCUSSION

An analysis of the results shows that mainly compressive stresses act in the bulk of the workpiece, which is confirmed by experiments and values obtained using the slip line (S.L.) method.

To assess the stress state during the deformation of workpieces in a closed die, the well-established method of slip lines was used [9]. According to the slip line method, a field of slip lines is constructed from the side of the central rams when they are inserted into the workpiece and lateral flat rams when moving backward due to the displaced metal into the orifice of the matrix (Figure 1).

The construction of the fields of the slip lines begins in the direction of movement of the lateral rams when the metal is displaced into the orifice of the matrix. It should be noted that the lateral rams are forced out when the central rams are inserted into the workpiece. From here, these sites can be taken free, because they move unhindered back relative to the central rams. On these contact surfaces, according to the properties of the method used, the slip lines should come out at an angle of 45° . In the area adjacent to the free areas at the nodal point 1,1, the slip lines intersect each other at an angle $\pi/2$ (orthogonality property). Hence, in the ΔAC zone (1,1), the stress state can be considered homogeneous.

Next, the construction of the S.L. fields extends to nodal point 0,0. For this, arcs are drawn from points A and C, with radii A (1,1), C (1,1). By the angle $\Delta\beta$. Replacing the arc with a straight segment, draw a perpendicular to this segment until it intersects with the X axis. If, the perpendicular intersects with the X axis at the central point 0,0, then the construction stops and the field of S.L. is considered to be correct. If, at the point 0,0, the S.L. does not intersect with the X axis, then it is necessary to change the value of $\Delta\beta$ and select this value so that they can intersect at the point 0,0.

In this case, the value of the angle of rotation of the S.L. $\Delta\beta$ was 35° , and with this value of S.L. intersected with the X axis at point 0,0. In a similar way, the hp field was built. and from the central rams. On the flat surfaces of the lateral rams S.L. should go at an angle of 45° , because friction forces are accepted on this surface as minimal. Further, construction continues until the intersection of S.L. with a nodal point 1,1. In this case, the angle of rotation of the hp $\Delta\beta_1$ is 25° .

Now, on the constructed S.L. field the average normal voltage at the nodal points is determined. For this, the Hankey ratios are used:

$$\sigma_{1,1} - \sigma_{1,2} = \pm 2k\Delta\beta,$$

where $\sigma_{1,1}$ and $\sigma_{1,2}$ are, respectively, the values of the average normal stress at the nodal points 1,1 and 1,2, MPa; k is the plasticity constant, which is $0,577\sigma_t$, σ_t is the yield stress of the treated body, MPa. Using this ratio, the average normal voltage at point 1,2 is determined, but at the beginning the average normal voltage at point 1,1 is determined. The average normal stress $\sigma_{1,1}$ at point 1,1 is determined by taking on the segment of the triangle ΔAC (1,1) uniform and from the condition of equilibrium of forces applied at the exit from the orifice of the die, i.e., on the AC segment:

$$\sigma_{1,1}(y_A - y_{1,1}) + kx_A = 0, \text{ hence}$$

$$\sigma_{1,1}y_A = -kx_A, \text{ and } \sigma_{1,1} = -k, \text{ b.t. } y_A = -x_A, y_{1,1} = 0.$$

Now, taking into account the average stress $\sigma_{1,1}$ at point 1,1, the average $\sigma_{1,2}$ stress at point 1,2 is determined:

$$-\sigma_{1,2} = k \pm 2k \cdot \Delta\beta, \text{ or } \sigma_{1,2} = -k(1 + 2 \cdot \Delta\beta),$$

and substituting the corresponding value of the rotation angle $\Delta\beta = 35^\circ$ it turns out,

$$\sigma_{1,2} = -k(1 + 2 \cdot (\pi 35 / 180)) = -k \cdot 2,221.$$

Suppose a steel workpiece is processed in a closed die. Then, for structural carbon steel, the yield strength at a temperature of about $700-5000^\circ\text{C}$ will be $\sigma_b = 220$ MPa, respectively, the average normal stress at 1.2 will be:

$$\sigma_{1,2} = -k \cdot 2,221 = 0,577 \cdot 220 \cdot 2,221 = -281,9 \text{ MPa, accept } 282 \text{ MPa.}$$

Similarly, the average normal stress at the nodal point 0,0 is determined:

$$\sigma_{0,0} - \sigma_{1,2} = \pm 2k\Delta\beta,$$

$$\sigma_{0,0} = -\sigma_{1,2} \pm 2k\Delta\beta,$$

$$\sigma_{0,0} = -282 - 2 \cdot 127 \cdot 0,610 = -436,94 \text{ MPa.}$$

Now through the average normal stress and the built field of s.l. the stress components at the nodal points are

determined. Definition starts at nodal point 1,1. using the basic ratios from theories of plasticity:

$$\begin{aligned} \sigma_{\varphi(n,m)} &= \sigma_{op.(m,n)} + k \sin 2\theta_{n,m}; \\ \sigma_{y(n,m)} &= \sigma_{op.(m,n)} - k \sin 2\theta_{n,m}; \\ \tau_{\varphi y(n,m)} &= k \cos 2\theta_{n,m} \end{aligned}$$

where θ_n, m - respectively the angles between the main axis and S.L. at the nodal points n, m , $\sigma_{op.}(m, n)$ is the average normal stress at the corresponding nodal points $n.m$.

Hence, the voltage components at the nodal point 1,1 ($n = 1, m = 1$):

$$\begin{aligned} \sigma_{x(1,1)} &= -k + k \sin 2\theta_{1,1} = -127 + 127 \cdot 45^\circ = 0 \text{ MPa}; \\ \sigma_{y(1,1)} &= -k - k \sin 2\theta_{1,1} = -127 - 127 \sin 2 \cdot 45^\circ = \\ &= -2 \cdot 127 = -254 \text{ MPa}; \end{aligned}$$

$$\tau_{xy(0,0)} = -127 \cos 2 \cdot 45^\circ = 0 \text{ MPa, where } \theta_{n,m} = \theta_{0,0} = 45^\circ.$$

Nodal point stress components 1.2 ($n=1, m=2$):

$$\begin{aligned} \sigma_{x(1,2)} &= -282 + k \sin 2\theta_{1,2} = \\ &= -282 + 127 \sin 2 \cdot (45-35)^\circ = -238,56 \text{ MPa}; \end{aligned}$$

$$\begin{aligned} \sigma_{y(1,2)} &= -82 - k \sin 2\theta_{1,2} = \\ &= -282 - 127 \sin 2 \cdot (45-35)^\circ = -325,44 \text{ MPa}; \end{aligned}$$

$$\tau_{xy(1,2)} = -127 \cos 2 \cdot (45-35)^\circ = -119,34 \text{ MPa, where } \theta_{n,m} = \theta_{1,2} = 10^\circ.$$

The stress components at the central nodal point 0,0 are also determined by the above ratios:

$$\begin{aligned} \sigma_{x(0,0)} &= -436,94 + k \sin 2\theta_{0,0} = \\ &= -436,94 + 127 \sin 2 \cdot 45^\circ = -309,94 \text{ MPa}; \end{aligned}$$

$$\begin{aligned} \sigma_{y(0,0)} &= -436,94 - k \sin 2\theta_{0,0} = \\ &= -436,94 - 127 \sin 2 \cdot 45^\circ = -563,94 \text{ MPa}; \end{aligned}$$

$$\tau_{xy(0,0)} = k \cos 2 \cdot 45^\circ = 0 \text{ MPa,}$$

where $\theta_{n,m} = \theta_{0,0} = 45^\circ$ – the angle between S.L. and the main axis X and Y.

The obtained values of the stress components are given in Table 1.

Table 1 **The components of the stress at the nodal points of the slip lines when processing balls in a closed die**

Stress	Values of stress components in nodal points/MPa		
	0,0	1,2	1,1
σ_x	-309,94	-238,56	0
σ_y	-563,94	-325,44	-254
σ_{op}	-436,94	-282	-127
$\tau_{\varphi y}$	0	-173,60	0

In addition to the theoretical method of slip lines, for reliability and comparison of the results of the study of the stress-strain state, mathematical computer modeling was used in the DEFORM 3D software package.

The initial temperature of the workpieces is 1 150 °C. The coefficient of friction on the tool is set to 0,5.

The equivalent strain and average normal stress are taken as the compared parameters of the stress-strain state. The simulation results - the distribution of these parameters over the cross section of workpieces with different ratios of the radius of the workpiece to its height are presented in Figure 2.

Equivalent deformation shows the degree of intensity of the development of the cast structure of the

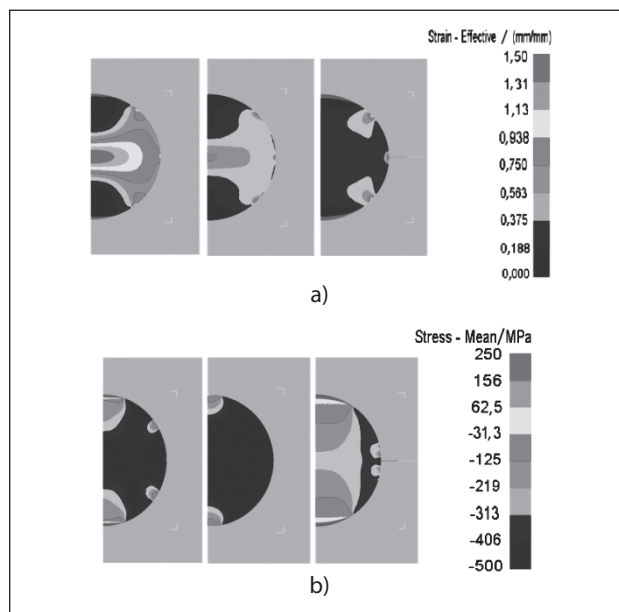


Figure 2 Distribution of stress-strain state parameters over the 3 workpieces section
a - equivalent deformation, b - average normal stress

workpieces. In accordance with the distribution pattern of this parameter, it can be seen that the most intensive study of the cast structure occurs where the difference in the values of equivalent deformation for different volumes of the ball is not so significant. In both cases, the deformation is concentrated in the central part of the workpiece. The greater value of the equivalent deformation parameter when using a workpiece with a large ratio of the workpiece radius to its height can be explained by a large tool stroke.

The average normal stress shows the general nature of the stress, where its negative values correspond to compressive and positive tensile stresses. When processing metals by pressure, the presence of tensile stresses is extremely undesirable, since they lead to a violation of the continuity of the metal and its further destruction.

Analysis of the obtained values of the stress components obtained by the theoretical method of S.L. and modeling when processing balls in a closed die shows that all the stress components, starting from the nodal point 1,1 at the exit from the orifice of the die, to the central nodal point 0,0, increase by 2-3,5 times. It should be noted that all compressive stress components contribute to the closure and brewing of all internal defects. In addition, the stress values obtained by the s.l. method and computer simulations are practically in equal limits. For example, the maximum average stress in the deformation zone obtained by the theoretical calculation method of slip lines is 436,94 MPa, and the value obtained by mathematical computer simulation is 500 MPa, which is quite acceptable under certain error conditions, primarily due to the difference in methods and properties of the selected material. A certain identity is observed in the forms of the deformation zone constructed by the slip line method and computer mod-

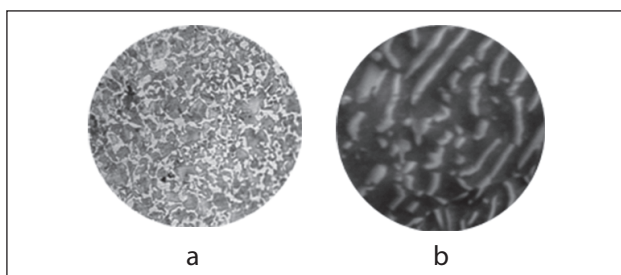


Figure 3 Steel structure after processing with an optical microscope (a), X 500 and an electron microscope (b), X 40 000

eling (Figures 1 and 2, b), where deformation localization is visible in the lateral and central regions. The study of the stress state allows you to determine the optimal value of the inserting of rams in the workpiece. Here, the important thing is not getting balls with recesses, but creating comprehensive compression, hydrostatic pressure in the volume of the ball. Therefore, the recess values may be small and the corresponding voltage values as large as possible.

Microstructure samples were also obtained (Figure 3).

An analysis of the microstructure of the sample obtained using an optical microscope included a grain counting method [10], which showed that the average grain diameter in the structure of the ball after processing compared to the original sample decreased by more than 3 times to an average value of 5 μm .

It is clearly seen in Figure 3b that the cementite plates or perlite layers (light streaks) are strongly fragmented and crushed. This is the main sign of a good implementation of intense deformation. The length of individual pieces of plates is from 0,5 μm to 1,5 μm . Significant grinding of grains in the transverse and longitudinal directions is observed, which leads to an increase in the strength characteristics of the material.

CONCLUSIONS

A new method for producing balls in a closed cavity of a closed matrix and the design of a closed die are proposed. The method of sliding lines proved the pos-

sibility of implementing intense plastic deformation in a closed die and the proposed method. Calculations of the stress-strain state of the workpieces by the slip line method and mathematical computer modeling show that the presence of compressive stresses in the deformation zone or comprehensive compression of the balls by alternate penetration in a closed die can contribute to the production of materials with a ground structure, and therefore with a better set of properties.

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Note: Translated by D. Rahimbekova, Temirtau, Kazakhstan