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Forging of a Hollow Ball Using a Deformable Insert Assembly

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ABSTRACT

The paper presents selected results of numerical analysis and experimental verification. The subject is the analysis of cold forging of a thin-walled hollow ball. The process of making a ball out of aluminum alloy and steel was considered. A distinctive feature of this process is the use of a special deformable insert assembly. It consists of two shaped expanding tubes, a distance ring and a centering tube. Each of these elements has a specific function, which was characterized in this article. Finite element analysis (FEA) simulation allowed proving the functionality of the insert assembly and comparing the cold forging of a steel and aluminum part, using the same inserts. Attention was also focused on the impact of the accuracy of the positioning of the insert assembly. Experimental verification confirmed the correctness of the modeling and complemented the results from FEA analysis.

Keywords: cold forging, hallow ball, steel, aluminum alloy, finite element analysis, experiment.

INTRIDUCTION

Hollow parts are readily used in mechanical engineering, aerospace, automotive and energy industries [1, 2]. On the one hand, such parts are lightweight, on the other hand, they perform a specific function. Such parts can be made by a variety of means. They can be cast, plastically shaped or machined. Using metal forming technology, hollow parts can be shaped from solid or hollow billets. Popular methods for shaping such products include forging, extrusion and rolling [3, 4].

Hollow ball forgings (including solid ones) are widely used in the construction of mechanisms and in components of hydraulic valves. Forging or rolling of solid parts does not cause major problems [5], although these processes are generally carried out under hot conditions. On the other hand, the shaping of hollow balls or near-spherical products already poses problems [5, 6, 7], especially under cold deformation conditions. The greatest challenge is to ensure steady forming conditions. When forging process is chosen, the problem is usually uncontrolled buckling of the billet [7, 8, 9] or unsatisfactory outline of the final part [10]. Another problem is the positioning of the workpieces in the dies and the subsequent removal of the forgings from the cavity of these dies. It is known from experience that ball forgings tend to jam in dies [10, 11].

This article presents a novel solution to the hollow ball forging process. The forging method is based on the use of a special assembly of deformable inserts, made of low-melting alloy. The choice of low-melting alloy is due to its significant suitability in the implementation of technological processes, as described, for example, in publications [11, 12]. Unlike the known technological solutions described in authors' earlier works [10, 11], the proposed insert assembly has a special alignment tube. Its function is to enable centering of the billet in the die cavity and then facilitate removal of the final forging from the die. Such a solution also makes it possible to fully automate the forging process, during its industrial implementation, for example, by making full use of the capabilities of manipulators. In the following part of this article, selected results of own research, based on finite element method (FEM) modeling and experimental verification, were presented.

SUBJECT OF ANALYSIS

The subject of the analysis is the cold die forging process of a hollow ball with an outer diameter of 30 mm, which is made from a thin-walled sleeve-shaped billet (the wall thickness is 1.8 mm) and has two central holes. In this process, dies of closed design are used, which have a spherical cavity with a radius of 15 mm. An overview photograph of this tools along with a sample of the ball forging is shown in Figure 1. A characteristic feature of this forging process is that additional deformable inserts in the form of an assembly are used during the making of the ball forging (Figure 2b). Its role is to: (i) center the workpiece in the die cavity, (ii) stabilize the part shaping conditions, and (iii) once the final part is complete, facilitate the removal of the one without damage. The tube protruding from the ball forging, which is part of the insert assembly (shown in Figure 1), makes it easier to remove the final forging from the die cavity in case of jamming. Figure 2 shows the shape and dimensions of the billet and the mentioned deformable insert assembly, which is placed inside the billet. This assembly consists of two outer expanding tubes (upper and lower – the so-called main deformable inserts), a distance ring and an inner aligning tube. The shape and dimensions of these components of the insert assembly are the result of optimization carried out by the author.

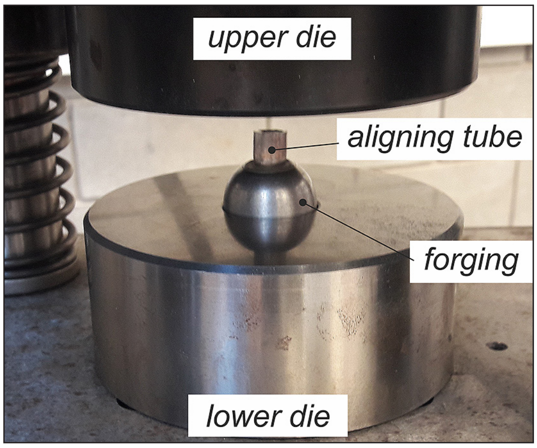

Figure 1. A photograph showing the tools and final ball forging

The scientific goal was to explore the conditions for shaping hollow sphere forgings using such a deformable insert assembly. The analysis also aimed to compare the forging of steel and aluminum parts using the same inserts, which are made of a soft material – Woode's alloy. On the other hand, the utilitarian purpose of using such a deformable insert assembly is to enable automation of auxiliary operations – i.e. placing the billet in the die cavity and removing the final forging from the dies. The advantages of using Woode's alloy to make deformable inserts and using only expanding inserts (without a aligning tube and distance ring) to forge an aluminum parts have been discussed in authors' earlier publications, such as [11].

NUMERICAL ANALYSIS

The numerical analysis was realized by the finite element method, using the Deform-3D program. Figure 3 shows a geometric model consisting of two dies, a billet and a deformable insert assembly (the same as in Figure 2). Geometric symmetry was used in the modeling to make more efficient use of computer computing resources. Dies were modeled as

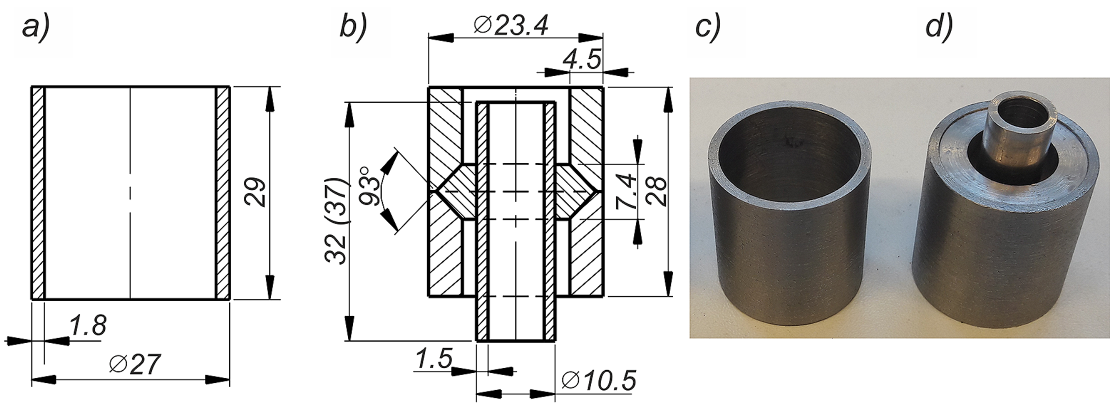

Figure 2. Shape and dimensions of the billet (a, c), the deformable insert assembly (b), and the view in the output configuration of the insert assembly placed inside the steel billet (d)

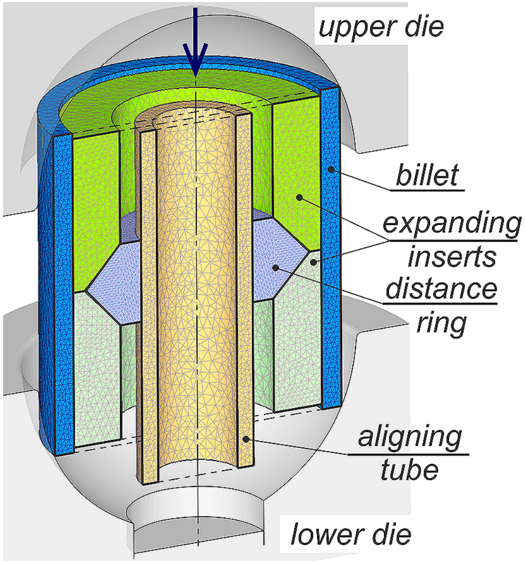

Figure 3. Geometric model used for finite element analysis (FEA) analysis – view of insert assembly located inside the billet and outline of dies

rigid objects, while deformable objects were modeled as rigid-plastic objects, which were discretized with tetragonal elements. The calculations assume that the top die moves at a constant velocity of 1.67 mm/s (according to the vector shown in Figure 3). Contact conditions are described by the Coulomb model, where the coefficient of friction is: μ=0.12 between tools and plastic objects, μ=0.12 between billet and insert assembly, and μ=0.09 between individual inserts inside the assembly, respectively. A material model representing the AlMgSi0.5 aluminum alloy and 19MnCr5 steel (two variants) was used to describe the behavior of the billet. Meanwhile, the deformable insert assembly was modeled with a material model representing the TBC12 alloy (BiPb25SnCd12). The flow curves of the modeled materials used in the numerical modeling, are compiled in Figure 4.

The numerical analysis included four variants of the configuration of the billet and deformable insert assembly (Figure 5). The base configuration is variant A (Figure 2, Figure 5a). Variant B (Figure 5b) represents the case where the aligning tube is protruded on both sides, which is intended to eliminate the problem of the ball forging accidentally remaining in the lower or upper die cavity. Meanwhile, variants C and D (Figures 5c, d) represent hypothetical cases of inaccurate mutual alignment of the insert assembly inside the billet in the output configuration (Figure 2d).

DESCRIPTION OF EXPERIMENTAL RESEARCH

The experimental research consists of two stages. The first stage is aimed at obtaining the necessary data needed for numerical modeling. The second stage is the experimental verification of the forging process, the purpose of which is to validate the FEM model and extend the results for the forging process under study.

First, flow curves were determined using the frictionless upset method for cylindrical samples (∅10 × 12 mm), the essence of which is approximated, for example, in the publication [13]. To eliminate the effect of friction, teflon grease was used. The results obtained from these tests are shown in Figure 4 earlier. The coefficients of friction were then determined according to the analytical and experimental method. For this purpose, ring specimens (∅25.5 × ∅12 × 9 mm) were upset, after which the specimens were modeled in FEM using previously determined material data. During the simulation of upsetting, the values of the friction coefficient were changed sequentially, aiming to obtain the dimensions of the upset rings that were identical to those of the experimental test. Experimental verification of the forging process was carried out using the tool set shown in

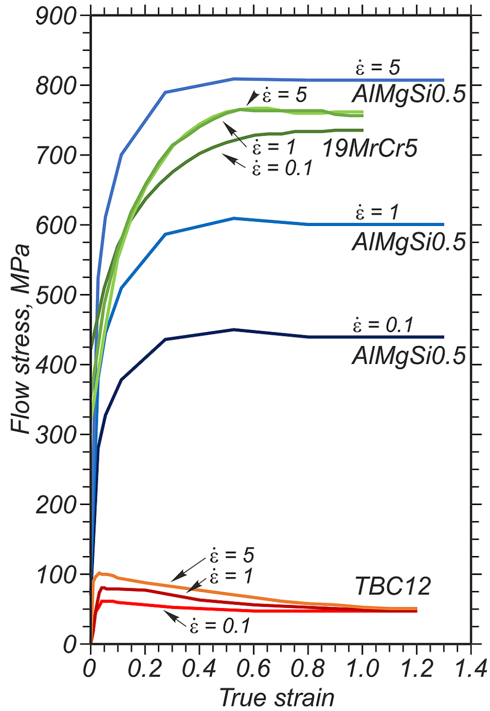

Figure 4. Flow curves for the three materials used in FEM modeling, determined for three values of strain rate **ε**

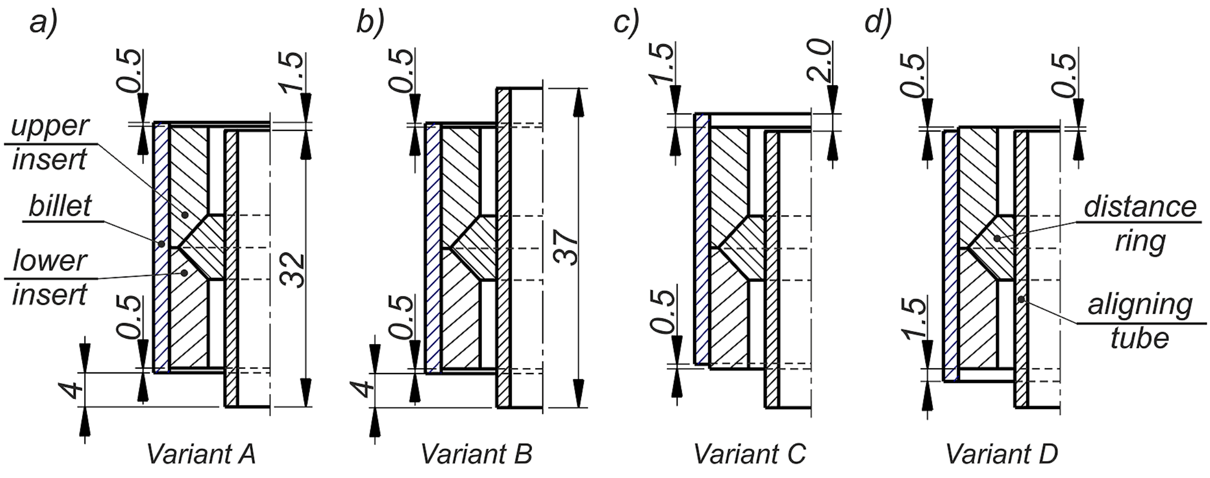

Figure 5. Four variants of mutual positioning of the components (expanding inserts, distance ring, aligning tube) of the insert assembly inside the billet

Figure 1 and the billet and insert assembly prepared as shown in Figure 2d. In the experiment, only variants A and C were considered (Fig. 2c). The billet (Fig. 2a) was made from the AlMgSi0.5 aluminum alloy in the softened state and the 19MnCr5 steel – these are the same materials used to develop the flow curves shown in Figure 4. An Inston testing machine with a maximum pressure of 1 MN was used. The forming force was recorded during the tests, and the obtained ball forgings were compared with the FEM results. During the tests, all the boundary conditions assumed during the numerical modeling were maintained. The basic study of the forging process of a steel parts was extended to include two additional cases in which only expanding inserts and no deformable inserts were used.

RESULTS OF NUMERICAL ANALYSIS AND EXPERIMENTAL VERIFICATION

Figure 6 shows the measured forming force of the aluminum ball according to variant C and the force measured in FEM (for all four variants). Comparing these results with each other, it can be noted that their qualitative and quantitative agreement is satisfactory. Modeling four variants of the alignment of the billet and insert assembly showed that the accuracy of their mutual alignment does not make any difference to the forming force.

The force measured in the experiment is slightly greater than the calculated one. In the first phase of shaping (i.e., before a clear change in the trend of the graph), the measured force is characterized by the “amplitude” of the change in value. This is due to the fact that the billet made of aluminum alloy tends to move unstably along the wall of the die cavity – slips are formed. A similar phenomenon was observed in earlier authors’ studies, discussed, for example, in publication [11]. In contrast, the subsequent intense increase in force values is due to the closing of the dies.

The next Figure 7 shows a force plot for the cases of forging a ball made of steel. In addition to the forming force for variant C (with the insert assembly), the graph also shows the force for the forging test without the mentioned inserts. Comparison of the results allows concluding that the use of additional inserts causes a clear increase in the force, but not so significant. In addition, it was shown that compared to the forging of an aluminum ball, the force during the forging of a steel ball is higher (as expected), and its course is more uniform. This means that the forging of the steel forging is more stable and there is no “slippage” phenomenon. Comparing with each other the results shown in Figure 6 and Figure 7, it can be concluded that the built FEM model provides the results that remain in satisfactory agreement with real results.

Figure 8 shows the results of FEM simulations of the aluminum ball forging process according to variant A. The essence of the presented forging process is to achieve the appropriate deformation of the expanding inserts, preferably according to the arrows (detail A). Such a scheme ensures proper and stable shaping of the ball forging. The role of expanding inserts is to prevent uncontrolled buckling of the workpiece, resulting

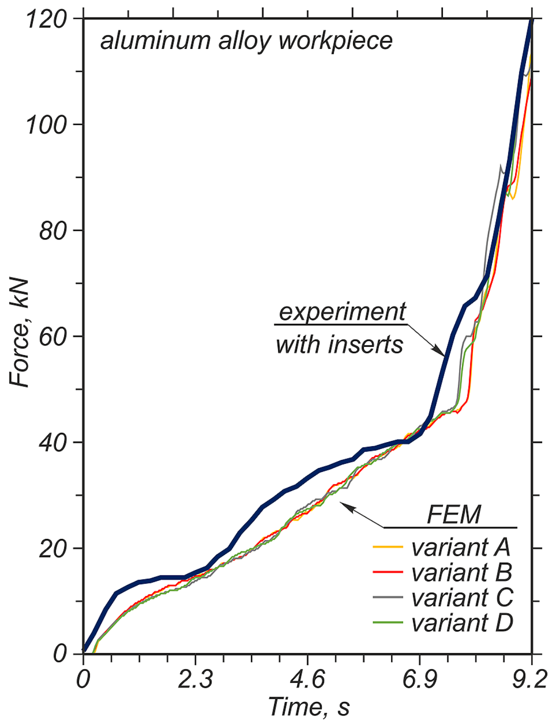

Figure 6. The force measured in the experiment and calculated in FEM for the forging process using a billet made of the AlMgSi0.5 aluminum alloy

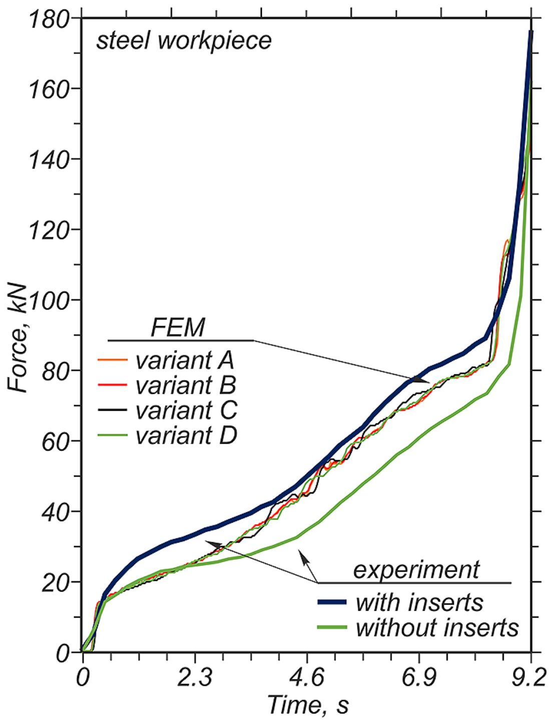

Figure 7. Force measured in experiment and calculated in FEM for forging process using a billet made of 19MnCr5 steel

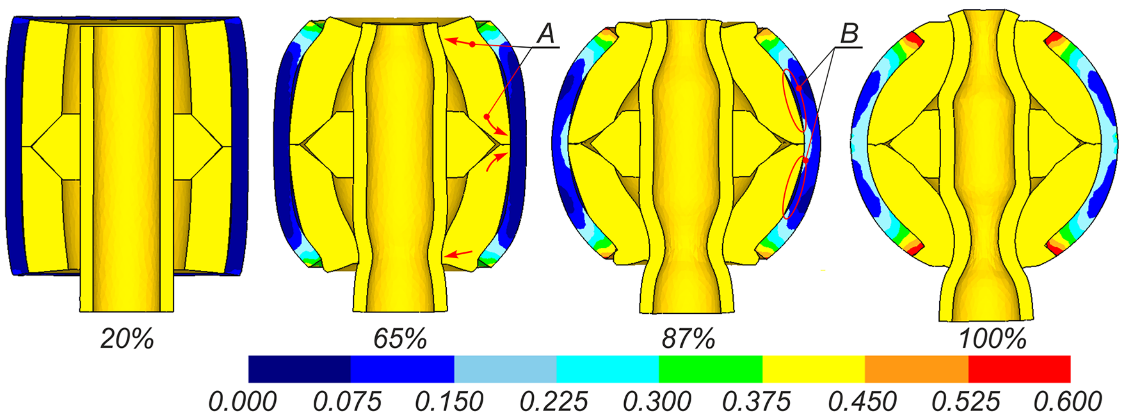

Figure 8. Shape progression and strain effective distribution in a ball forging made of aluminum alloy

from significant slenderness of billet (i.e. small wall thickness). The resulting strain distribution calculated for the aluminum forging (Figure 8) is typical. A similar distribution was obtained during the forging process using only expanding inserts – results for such a case were published earlier in authors' own works [10, 11]. Figure 8 also shows that the distance ring and aligning tube used do not interfere with the forming of the ball forging. The role of these two elements is to pre-center the billet in the die and to facilitate the removal of the final part from the die. As it can be seen in Figure 8, the aligning tube undergoes a favorable deformation, forming the so-called locking. On the other hand, the distance ring, in principle, does not have any significant influence on the process of shaping the ball forging. Instead, it fulfills a fundamental role – it holds all the components of the insert assembly.

Meanwhile, Figure 9 shows the results of FEM simulations for the case of a steel forging process. Comparing them with the results in Figure 8, it can be said that qualitatively and quantitatively they are similar. The differences are basically in two aspects. During the shaping of the aluminum ball, a significant gap is formed between the forging and the insert at some stage (detail B in Figure 8), and then disappears. In contrast, when forming a steel ball, such a gap occurs all the time, but it is insignificant. Through this, the conditions of ball forming are more stable, and the effect of the inserts on the workpiece is more continuous. In addition, when forging a steel ball, small dead zones are formed in its cross-section – detail C in Figure 9.

The FEA analysis also included the effect of insert assembly setup on the final shape and dimensions of the ball forging. The results, which apply to the forging process of an aluminum ball, are shown in Figure 10. Attention was drawn to the height of the forging and the diameters of the two holes in this forging. The maximum diameter of the forging was equal to 30 mm, based on the complete filling of the die cavity. It was noted that the choice of the pre-alignment variant of the insert assembly has a significant effect on the diameter of the holes in the forging. This results in asymmetry of the obtained hollow sphere. A slight asymmetry also occurs for variant A, when the insert assembly is exactly aligned inside the billet. On the other hand, any additional offset of the components of the insert assembly from each other projects a worsening of the mentioned asymmetry of the forging.

Similar conclusions were obtained for the forging process of a steel forging, as shown in Figure 11. However, a steel forging has a greater height than an aluminum forging. This dimension is basically no different from the initial setting of the insert assembly. The hole at the top of the steel ball forging is smaller than that of an aluminum ball. The bottom hole, on the other hand, has a larger diameter than for an aluminum forging. The exception is variant C. This is due to the fact that the inserts are made of soft Woode's alloy, so they nevertheless exhibit less resistance to deformation of the steel forging than was observed for the aluminum forging.

An example of making an real aluminum ball according to variant C is shown in Figure 12. The obtained ball forgings along with deformed inserts were cut, showing the outline in cross-section. It was observed that the aligning tube undergoes its first deformation only

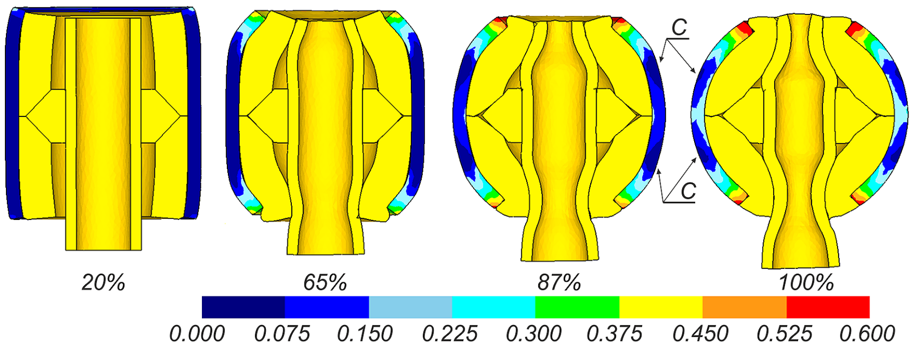

Figure 9. Shape progression and strain effective distribution in a ball forging made of steel

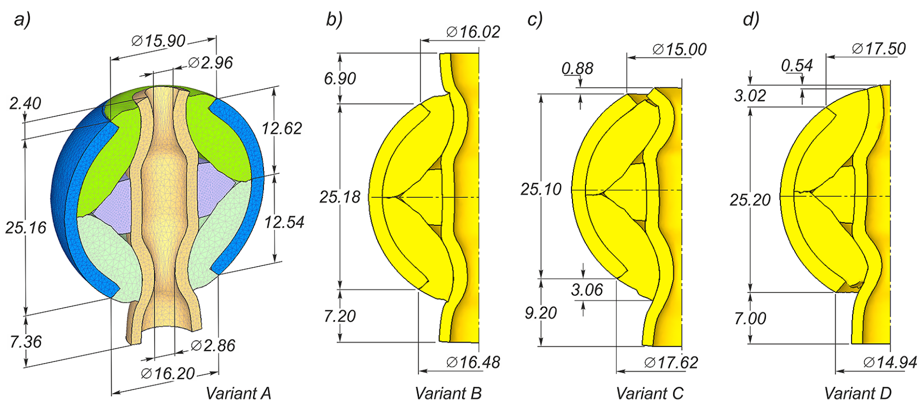

Figure 10. Shape and dimensions of the forging made of aluminum alloy and deformed inserts depending on the variant of the insert assembly setup

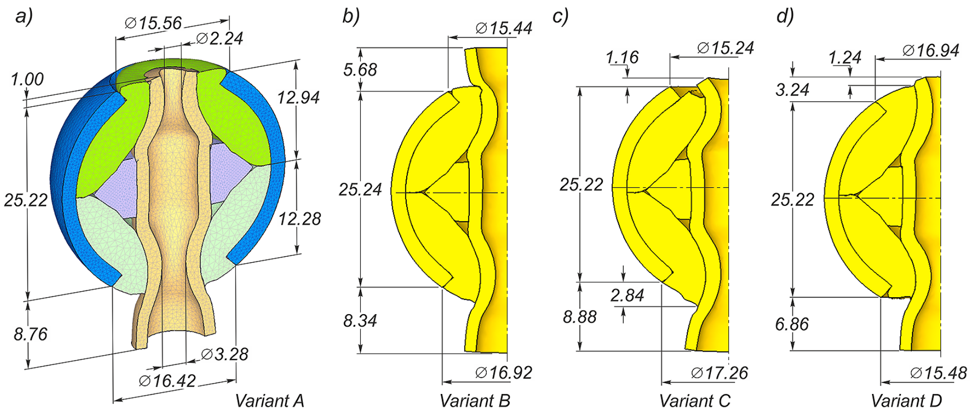

Figure 11. Shape and dimensions of the forging made of steel and deformed inserts depending on the variant of the insert assembly setup

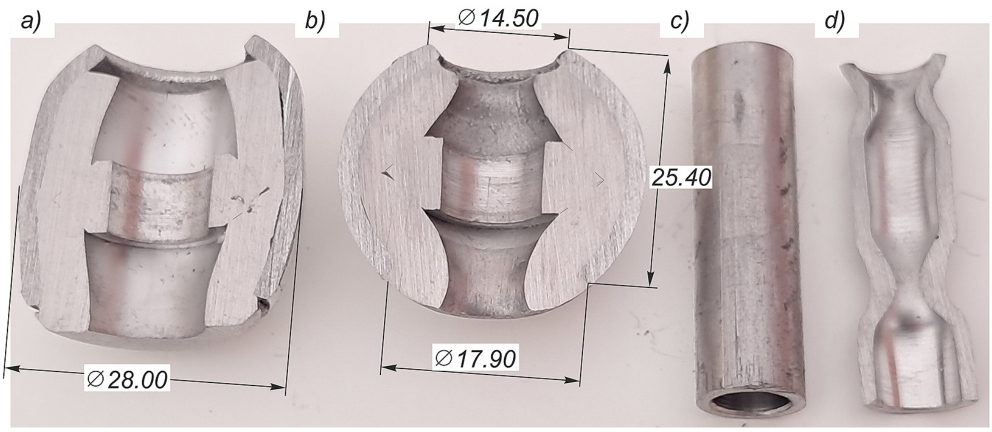

Figure 12. Example of aluminum ball making according to variant C and deformed inserts: a) and b) 45% and 100% process advancement, respectively, c) and d) shape of aligning tube at 45% and 100% process advancement, respectively

halfway through the forging process. By this stage, its position inside the workpiece may have changed, and it may even slide out completely (Figure 12c). Hence, it follows that a proper tight fit between the aligning tube and the distance ring is recommended. In addition, it was observed that deliberately moving the entire insert assembly downward causes the top hole of the forging to start forming quite quickly. The resulting collar is wrapped inward. However, this does not prevent the final outline of the ball forging from being correct, as shown in Figure 12b. Comparing these experimental results with FEM calculations (Fig. 10c), there is considerable qualitative agreement as to shape and dimensions. Although the numerical difference between the characteristic dimensions is clear, it can be concluded that the correctness of the FEM model construction has been confirmed by experiment, and the proposed forging process is feasible.

Figure 13 shows an axial cross-section of a steel ball forging with deformed inserts. Three ball forgings were compared, which were made according to variant A, using only expanding inserts and without using any deformable inserts. The resulting outline of the first forging and the inserts used (Figure 13a) is in good agreement with the FEA results shown in Figure 11a. This allows concluding that the developed FEM model is qualitatively and quantitatively correct. When comparing the characteristic dimensions, it can also be concluded that the numerical agreement between experiment and modeling is better compared to the case of the aluminum ball forging process. It was also noted that when shaping a steel ball forging, the quality of the outer surface of this

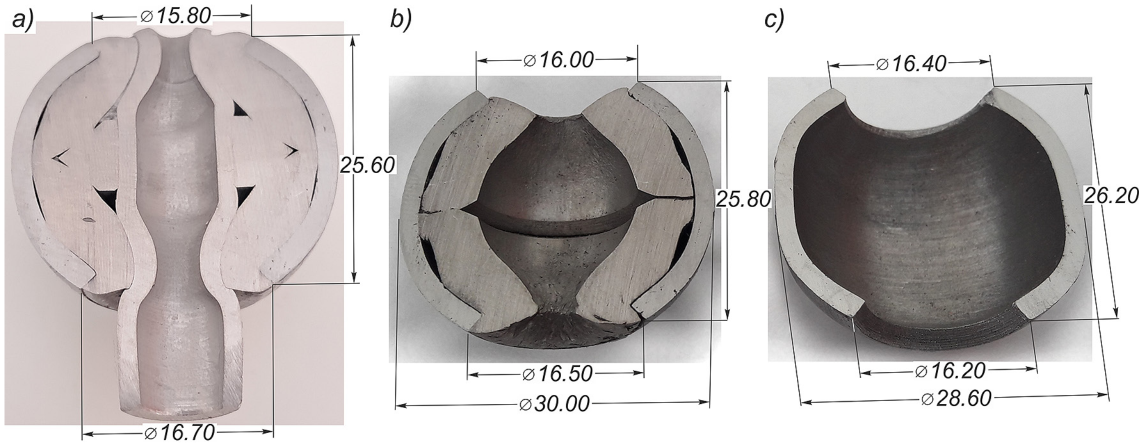

Figure 13. Example of making a steel ball according to variant A (a), using only expanding inserts (b) and without using any deformable inserts (c)

ball is better than for aluminum forging. The steel does not tend to flow into the space between the dies. In addition, it was observed that the boundaries between the surfaces of the inserts and the inner ball were clearer (Figure 13). The forging process carried out using only expanding inserts (Figure 13b) also produces a steel forging with the correct outline. On the other hand, trying to forge this part without the use of deformable inserts (Figure 13c) does not provide a ball forging with the desired outline. This confirms the necessary use of deformable inserts in the presented technological process.

CONCLUSIONS

The article presents a new technological solution involving the use of a special insert assembly. The forging process of steel and aluminum forgings was analyzed. The obtained results of simulation and experimental verification allow drawing the following final conclusions:

Deformable inserts provide stable forging shaping conditions, they also cause an increase in forming force compared to forging process without inserts, but this increase in force is not large enough to be significant;

Adding a distance ring and aligning tube to the insert assembly does not interfere with the proper function of the expanding inserts, so the stability of the forging's shape is maintained, and the workpiece does not buckle;

The aligning tube ensures proper alignment of the billet in the die cavity, and undergoes favorable deformation during forging process, by guaranteeing harmless removal of the final ball from the die when it becomes jammed;

Deformable inserts made of Woode's alloy can be successfully used to forge balls made of relatively soft materials (such as aluminum) and relatively hard materials (such as steel);

The correct alignment of the insert assembly with each other has an impact on the quality of the final ball forging, which manifests itself in the disparity of hole diameters in this forging.

Acknowledgements

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