



A cold forging process for producing thin-walled hollow balls from tube using a plastic insert

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Abstract

This paper investigates a cold forging process for producing hollow balls made of an aluminium alloy. The forging with an outside diameter of 30 mm is formed from a tube section with a 2-mm wall thickness. Preliminary tests have shown that in traditional die forging, the use of a billet with such a small relative thickness not only limits the range of applicable geometric parameters but also causes buckling. The authors propose to solve this problem by using an additional tool that has an active effect on the inner surface of the workpiece, and thus makes it possible to control the forging process conditions. The tool is a plastic insert, i.e., an additional flexible core made of a low-melting alloy. Theoretical and experimental results presented in this paper provide a considerable insight into the cold forging process for thin-walled hollow balls. The effects of the plastic insert geometry and dimensions on the forging process are also examined. A solution is proposed to ensure that the forged part meets all requirements.

Keywords (Thin-walled) hollow ball · Die forging · Cold forging · AlMgSi0.5 alloy · Plastic insert

1 Introduction

In the era of energy-saving technologies, machine components characterized by low weight and high relative strength are of vital importance. This group of machine components undoubtedly includes hollow products [1–3] that are “empty inside” during and after the forming process. Hollow products can generally be divided into thick- and thin-walled parts [4].

Thick-walled parts are easy to form. There are numerous effective techniques for manufacturing such products. These include both forging methods [4–6] and rotary forming methods, e.g., [1, 7, 8]. Technological problems arise when forming thin-walled parts [4]. The authors suggest dividing thin-walled parts into two groups, depending on whether their

wall thickness is lower or greater than 2 mm. Thin-walled machine parts with a wall thickness lower than 2 mm can be formed from sheet metal plates [9] or thin-walled tubes. To this end, the hydroforming method is most often used, in which the process stability is ensured by high-pressure liquids [10]. An alternative to liquids is the use of flexible media [11, 12], e.g., those made of elastomers. Additional rigid tools such as mandrels are less and less widely used [2, 13]. An alternative to the above-mentioned techniques for producing thin-walled parts are the methods based on the lightweight design philosophy [14–16], according to which the inside of the workpiece is filled with some other lightweight and plastic metal. In connection with this, it should be mentioned that this philosophy provided an inspiration for the development of a forging process for hollow balls proposed in this paper.

A literature review shows that hollow parts having a wall thickness of at least 2 mm are an interesting group of products. Such products are usually treated as typical forgings and are usually formed from either seamless tubes or extruded solid billets, using methods in which the inner surface of the workpiece is deformed in a free-form manner (i.e., without the use of additional tools), such as compression [3, 7, 8], cross wedge rolling, rotary extrusion [5] and extrusion [6]. Deformation of the inner surface of the workpiece can be controlled, e.g., by using an additional rigid tool (e.g., a mandrel) in the forming

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process such as forging [13], orbital forging [5] and rotary compression [2]. Hollow forged parts can be produced at room temperature (i.e., cold forged) by the hydroforming technique, which unlike classical hydroforming methods, involves the use of flexible mandrels (made of e.g. polyurethane) instead of liquids [12, 17]. However, Alzahrani [10] has shown that hydroforming can also be effectively performed using liquids. Steel forgings are often formed at elevated temperature by the hydroforming technique according to the method described by Chavdar [14, 15] and Goldstein [18]. This method involves the use of an aluminium core that behaves like a liquid when formed at temperatures above its melting point. After the forming process, the aluminium core is not removed but is left inside the finished product [19, 20]. For this reason, cores are only made of light metals and alloys whose melting points are lower than their forging temperature ranges. When producing parts made of aluminium alloys, the hydroforming process can be performed according to the method proposed by Graf [21], in which a polyamide core is heated up to a temperature at which it does not melt; at the same time, however, this temperature is below the forging temperature range.

The problem of producing thin-walled parts was also raised by Tekkaya [16], who presented possible technological solutions and discussed their features. It can be assumed that the choice of a forming technology depends on many factors, in particular the shape and dimensions of the finished part, forming conditions and the possibility of preventing standard failure modes (e.g., excessive thinning of the workpiece wall, cracks, buckling, etc.) [3, 4, 7, 16, 17, 22]. If the deformation resistance of a material is relatively low, the forming process can be carried out at room temperature. Given the subject matter of this paper, the authors focus on cold forming processes. As it is widely known, flexible cores made of elastomers can be effectively used in cold forming processes. Unfortunately, these materials do not always exhibit the required resistance, and their characteristics (flexibility) do not always ensure stable forging conditions. Elastomers tend to give up accumulated energy in various ways, e.g., through uncontrolled flow or elastic strain [11]. Following a critical analysis of all known technological solutions, the authors came to a conclusion that these problems can be solved to a great extent if the cold forging process is performed using a plastic core (insert). Matveev [23] and Sokolov [24] proposed similar technological solutions for forging balls. Unfortunately, the available literature does not provide detailed descriptions of these solutions.

In light of the above, a fundamental question arises: What material should this additional tool be made of? What is more, another question can be posed: What shape should this insert have to ensure optimal forming conditions? There are solutions in which lead is used. Given the weight of lead, however, such cores must be removed. This poses no difficulty in the case of products with simple geometries, but becomes

troublesome when products with complex shapes are forged, e.g., balls. The authors propose a solution in which the plastic insert is made of a low-melting lead-based alloy, because lead can easily be removed from the forged part and then used again. Alloys of this type are popular and widely used in the engineering industry for other purposes than just as alloys for precise casting. They are used in the manufacture of technological tools, among other things. For example, Wang [25] used a low-melting alloy to make an additional tool (chuck) in the cutting process for a thin-walled cover. In [26], Wang used low-melting alloys as plastic inserts in the extrusion process. The most important conclusion to be drawn from the above literature survey is that the use of inserts invariably improved the technological process conditions and reduced the operating costs.

2 Problem description and preliminary analysis

This paper investigates a cold forging process for producing thin-walled hollow balls made of an aluminium alloy. It is assumed that a ball with a nominal outside diameter D of 30 mm will be formed from a tube with an initial height h_0 and an outside diameter d_0 , having an initial wall thickness g_0 of 2 mm. A schematic design of the analysed process is shown in Fig. 1. The authors have decided to use the cold forging method because it gives rise to forged parts with increased strength due to work hardening, which is in line with the aforementioned tendency towards producing lightweight parts with the highest possible relative strength. Another rationale for selecting this forming method stemmed from the need to eliminate the operation of billet preheating, as this—given the relatively small wall thickness of the billet—might prove ineffective or even pointless.

A similar forging process was investigated by the authors previously, and the results were presented in [4]. The study investigated the formation of a steel ball from a tube for two variants of the billet wall thickness (g_0 3 mm and 4 mm). In [27], a forging process for producing an aluminium alloy forged part with similar dimensions was described. The above studies [4, 27] also describe and discuss typical failure modes in forging processes for such parts. A comparison of previous research results reported in the cited works with the results of preliminary studies on the analysed problem (i.e., forging balls from a thin-walled billet) demonstrates that it is more difficult to ensure stability of the forging process under these conditions. This was particularly true when balls were formed from a billet that had similar overall dimensions but a smaller wall thickness, i.e., g_0 was equal to 2 mm.

Figure 2 shows the forged hollow balls obtained in the experiments carried out with the use of the equipment shown in Fig. 1c. A tube section with the initial dimensions of $d_0 =$

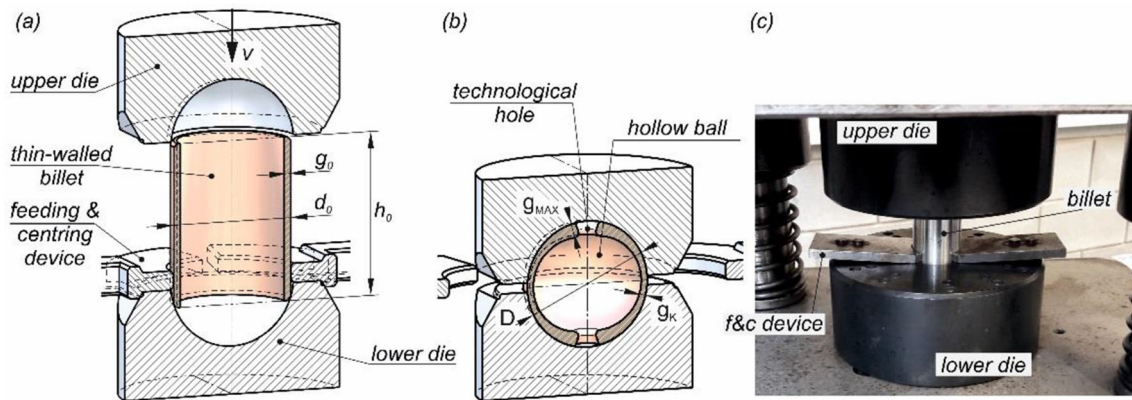


Fig. 1 Schematic design of the analysed forging process for a hollow ball: (a) beginning of the process, (b) end of the process and (c) real view (detailed description is given in the text)

26 mm and $h_0 = 31.4\text{--}37.2$ mm was made of aluminium alloy AlMgSi0.5. It should be noted that the above dimensions of the tube correspond to the boundary conditions adopted by the authors in their previous studies ([4, 27]). As a result, it was possible to compare the effect of changing the wall thickness of the billet on the forging process. The results demonstrated that a reduction in the billet wall thickness made it impossible to forge parts with the desired shape. This was primarily due to excessive slenderness of the billet, and in the case of billets with smaller wall thickness, buckling would invariably occur. In extreme cases, a total collapse of the tube wall was observed locally (Fig. 2d); this defect did not, however, occur in the balls that were formed from the billet having a thickness of e.g. $g_0 = 3$ mm [27]. It was also observed that the application of the initial diameter d_0 of 26 mm and the reduction of the tube height h_0 to 31 mm (compared to the results reported in [27]) did not significantly improve the forming conditions. Moreover, it resulted in underfill (an example of this is shown in Fig. 2a).

Given the results of preliminary studies and their comparison with the results obtained by the authors in previous studies [4, 27], it is considered justified to conduct further research with a broader scope. The research will have two objectives: a cognitive one, which is aimed at obtaining extensive knowledge about forming conditions in the analysed forging process for thin-walled parts, and a utilitarian one that is aimed at

developing a technological solution enabling the production of forgings with the desired geometry.

3 Forging process without the use of a plastic insert

3.1 Description of the investigated process and the proposed method

This theoretical and experimental study investigated the forging process for producing a hollow ball with a target outside diameter d_k of 30 mm from a tubular billet with an initial wall thickness g_0 of 2 mm. A schematic of the analysed process is shown in Fig. 1. The scope of analysis involved experimental tests of forging cases for different values of the billet dimensions (d_0 , h_0) in order to verify the developed numerical model and validate theoretical results. The experiments were carried out in laboratory conditions using the tools shown in Fig. 1c and the Instron testing machine with a maximum load of 1 MN and a constant maximum die velocity of 1.67 mm/s. During the experimental tests, the motion of the tools was controlled by means of a computer program that additionally recorded strength and kinematic parameters of the process. Prior to feeding the billet, the die cavity was lubricated (the chemical composition of the lubricant is a trade secret). The



Fig. 2 Examples of hollow balls formed from a tube with a thickness g_0 of 2 mm, an outside diameter d_0 of 26 mm and heights h_0 of (a) 31.0 mm, (b) 31.7 mm, (c) 34.4 mm and (d) 37.2 mm, respectively (the balls shown in this figure were obtained in preliminary studies)

billet was made of commercial aluminium alloy AlMgSi0.5 in the annealed condition (EN Al-6060-O in compliance with the PN-EN 573-1: 2004 standard).

A theoretical analysis was performed using the Deform-3D software that is based on the finite element method. A geometric model of the analysed forging process is shown in Fig. 3a. The model consists of two rigid objects (tools) and one discrete object as a tubular billet that is divided into

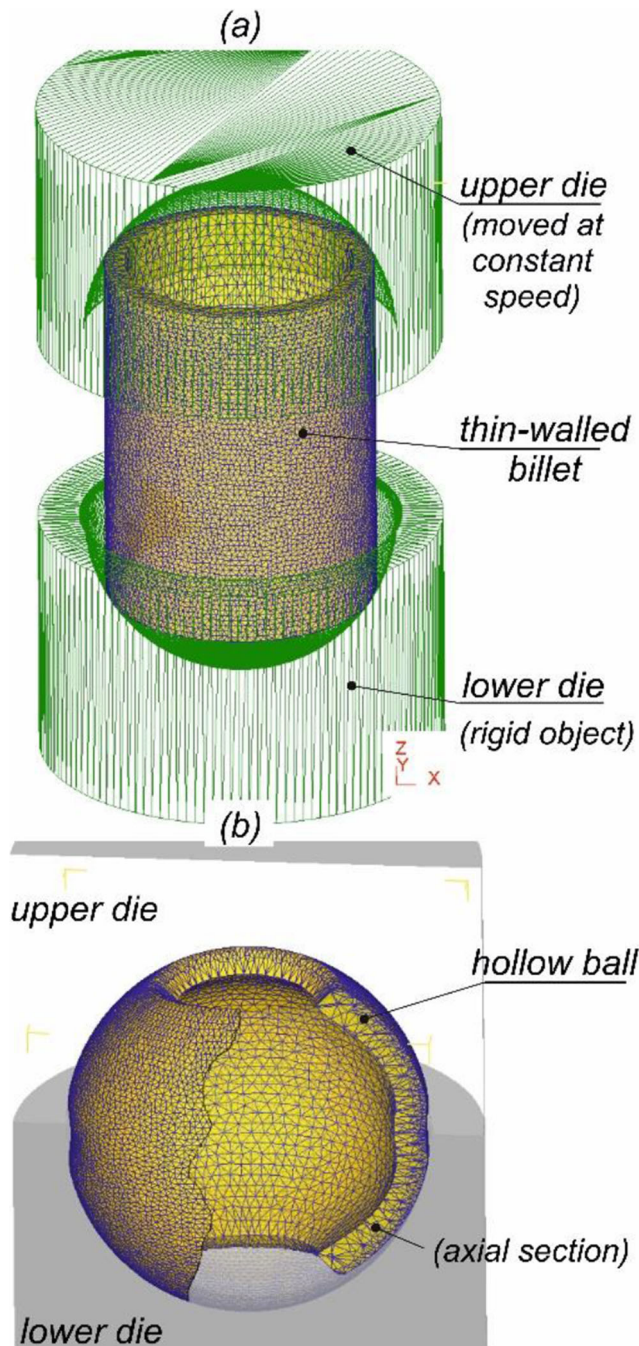


Fig. 3 Geometric model of the forging process for a hollow ball simulated by FEM (a) and an example of a forged hollow ball (b); description in the text

approximately 200,000 tetragonal elements. It was assumed that the ball (Fig. 3b) would be forged using a hydraulic press with the upper die velocity v maintained constant at 1.67 mm/s. The material model of the analysed aluminium alloy can be described by the following constitutive equation [27]:

$$\sigma_p = 949(0.0001 + \varphi)^{0.248} \exp(-0.5209\varphi) \dot{\varphi}^{0.1358}, \quad (1)$$

where σ_p is the flow stress, φ is the effective strain and $\dot{\varphi}$ is the strain rate.

In addition to that, friction was described by the Coulomb model with the coefficient of friction between the workpiece and the tools set equal to $\mu = 0.24$, which corresponds to the lubrication conditions applied in the experimental tests (the friction coefficient value was determined in previous tests). All material data and models of simulated conditions were obtained in previous studies, as described in [27]. In short, Equation (1) was obtained using a self-made computer program, with the data determined in plastometric tests of upsetting cylindrical samples on a testing machine under frictionless conditions. The coefficient of friction was calculated in ring upsetting tests.

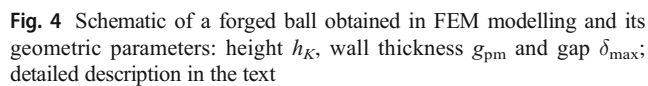
As shown in Fig. 1a, in the analysed cases, the billet diameter d_0 was changed from 26 mm to 29.5 mm, while the billet height h_0 was changed from 20 mm to 34 mm. Numerical simulations were performed for the entire range of tested variables. On the other hand, experimental tests were carried out only for several selected cases to verify the numerical results. The billet used in the experiments had an initial height h_0 equal to 26 mm or 27 mm and a diameter ranging from 27 mm to 28.5 mm that was changed every 0.5 mm.

3.2 Results and discussion

Obtained numerical results were analysed. Particular attention was paid to the quality of a forged ball (Fig. 3b), and it was proposed that geometric parameters be used for quantitative assessment. These parameters, according to Fig. 4, were the forging height h_K , the wall thickness g_{pm} measured on the parting line, and the one-sided gap δ_{max} measured between the lateral surface of the workpiece wall and the die cavity. A positive value of the parameter δ_{max} describes the degree of underfill. On the other hand, its negative value describes the degree of flash, and is thus tantamount to the overfill caused by the material flow between the upper and lower dies before they come into contact. The most favourable situation is when the value of δ_{max} is positive and as close to zero as possible.

It should also be emphasized that it is expected that the forged ball will have the highest possible height h_K while its wall thickness g_{pm} will be as close as possible to the initial value, i.e., $g_0 = 2$ mm.

Figure 5 shows the diagram with the coordinates of initial height h_0 and diameter d_0 of the billet alongside a symbolic



When the forging process is carried out in favourable (stable) conditions, two failure modes may occur and thus prevent obtaining a ball with the desired shape (i.e., the correct shape profile when considered in the axial plane; Fig. 3b). The

A detailed list of $\delta_{\max}$ parameter values calculated in the simulations, depending on two coefficients of billet slenderness (responsible for the occurrence of local or global buckling [4, 22, 27]), is given in Fig. 7. This plot clearly shows that obtaining a ball with the smallest possible value of the $\delta_{\max}$ gap is not an easy design task. For example, an increase in the billet height h_0 requires an increase in the diameter d_0 . However, the change of this diameter, assuming that the billet thickness g_0 is constant, significantly reduces the number of possible combinations of h_0/d_0 values. One could ask why the

Table 1 Qualitative assessment of a forged ball (description of the denotations used in Fig. 5)

Denotation	Description
+++	The most favourable forming conditions—the ball profile is correct and free from any defects; $\delta_{\max} < 0.2$ mm
++	Stable forming conditions; the ball profile is convex with slight equatorial flattening (i.e., near the parting line); $0.2 \text{ mm} < \delta_{\max} < 0.6$ mm
+	Stable forming conditions; the ball profile is convex with clearly visible equatorial flattening; $0.6 \text{ mm} < \delta_{\max} < 1.0$ mm
+/-	Relatively stable forming conditions; slight strain of the workpiece can be observed; the ball profile is convex, with considerable equatorial flattening; $\delta_{\max} > 1.0$ mm
++/P	Relatively stable forming conditions; the ball profile can be considered correct, but the dies are hard to close due to premature fill of die cavity with material
+/P	The same as above, but the ball profile is less satisfactory
G/++	Boundary forming conditions—buckling may, but not necessarily, occur; the ball profile should be correct
G/+	Boundary forming conditions—buckling may, but not necessarily, occur; it is less probable that the ball profile will be correct
G/P	Boundary forming conditions—buckling may occur; premature fill of die cavity (overfill) may occur
G/PP	The same as above, with clear overfill obstructing the closure of the dies
W/Z	Unstable forming conditions, buckling occurs—the ball profile is incorrect; as the simulation is continued, the die cavity is filled (in the real process, a defect shown in Fig. 2d occurs; the numerical results do not reflect the real process conditions)
W/Zr	The same as above; additionally, a local wall thickening is observed in the vicinity of the parting line
W/P	Unstable forming conditions, buckling occurs—the ball profile is incorrect; as the simulation is continued, overfill occurs and a local wall thickening of the workpiece is observed
W/PP	The same as above, considerable overfill results in the formation of flash
W/-	Unstable forming conditions, buckling occurs—the ball profile is incorrect; as the simulation is continued, underfill occurs with the ball flank becoming concave (FEM results accurately reflect the real process conditions shown in Fig. 2d)
WW/-, WWW/-, WW/Z, WW/Zr	The number of letters W denotes the degree of buckling and thus the extent of surface defects

billet height h_0 should be increased. An answer to this question is given in Fig. 8 that shows the effect of the billet geometry on the possibility of obtaining a forging with the required height h_K . The design objective is to achieve the highest possible value of h_K . It can be seen from Figs. 7 and 8 that there is

a very narrow range of the billet dimensions that ensure stable forming conditions and production of a forging with the desired shape.

It should also be mentioned that when the forging conditions are unfavourable, i.e., they are boundary or unstable, it is

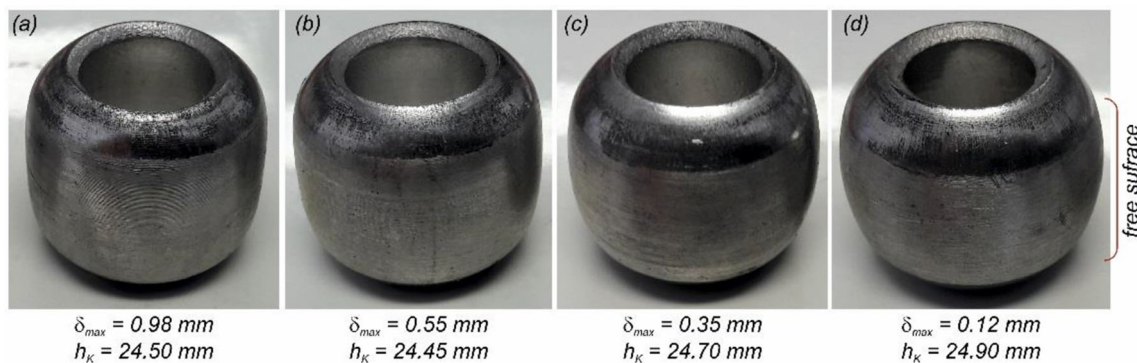


Fig. 6 Shape and key geometric parameters of balls produced in the experiments from a billet with the following dimensions: (a) $d_0 = 27$ mm, $h_0 = 26$ mm; (b) $d_0 = 27.5$ mm, $h_0 = 26$ mm; (c) $d_0 = 28$ mm, $h_0 = 27$ mm; (d) $d_0 = 28.5$ mm, $h_0 = 27$ mm

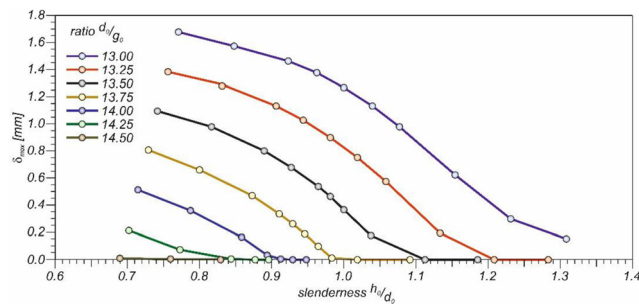


Fig. 7 Billet geometry (expressed by the slenderness ratio h_0/d_0) versus $\delta_{\max}$

impossible to obtain a forge part with the correct shape. When the slenderness ratio h_0/d_0 is unfavourable, buckling occurs. On the other hand, an increase in the d_0/g_0 ratio leads to a higher probability of overfill. Moreover, as shown in Fig. 9, in the above cases, one can observe excessive local wall thickening of the forged ball (quantified by the g_{pm}/g_0 ratio). The degree of wall thickening depends more on the change in the d_0/g_0 ratio rather than on the change in the h_0/g_0 ratio.

Summing up this subsection, it can be stated that the FEM results and the experimental findings demonstrate that in some cases (in Fig. 5 these cases are marked with the letter G), it is possible to obtain a ball with the desired shape. The authors believe that the forging process can be improved to completely eliminate or at least considerably reduce the occurrence of buckling. As a result, it will be possible to use billets with bigger dimensions and still obtain balls with the required shape. This conclusion is a motivation for further research on the analysed forging process for producing hollow balls. This time, however, the forging process is performed with the use of a plastic insert to improve its effectiveness.

4 Forging process with the use of a plastic insert

4.1 Description of the proposed forging process and method

Based on the results discussed in the previous section, the authors decided to modify the forging process for hollow balls shown in Fig. 1. The modification involved using an additional tool ensuring better control of deformation of the billet. The tool was a plastic insert, i.e., an additional core made of a flexible material. A schematic design of the modified forging process for balls is shown in Fig. 10. The insert was assigned the material properties of low-melting alloy TBC12 (BiPb25Sn12Cd12) [28, 29]. This material was chosen for two reasons: its plastometric similarity to technically pure lead and low melting point (below the boiling point of water). As a result, such insert will have the required deformation resistance, and following the forging process, the deformed core

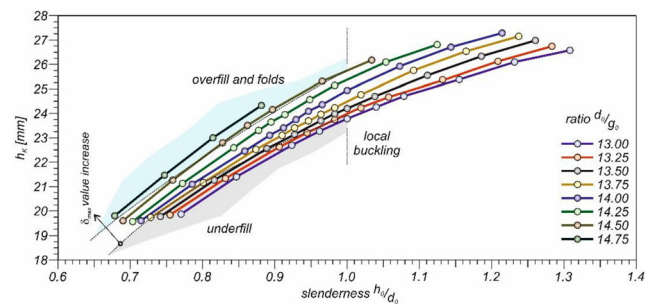


Fig. 8 Billet geometry (expressed by the slenderness ratio h_0/d_0) versus h_K and three main failure modes in the analysed forging process

can easily be removed from the forging and used again. The TBC12 alloy also has the desired casting characteristics [30], which ensures trouble-free execution of inserts with the required shape and dimensions.

The first and intuitive choice with respect to the shape of a plastic insert was a tube with a constant cross section, as shown in Fig. 11a. The choice of that shape was also motivated by a literature review in which such solutions were proposed, e.g., [23, 24]. Nevertheless, a detailed numerical analysis (which is discussed later on in the paper) showed that it was not the best choice. Therefore, the authors began to search for such insert geometry that would ensure optimal forging conditions and the achievement of the set objective and at the same time would be easy to make. These searches took account of the results of earlier studies, in particular with respect to the pattern of material flow during the forming of a hollow ball. The end result of these searches is the insert with the geometry shown in Fig. 11b.

Hence, the next stage of the theoretical and experimental study concerns the determination of the effect of the plastic insert dimensions on the conditions of forming hollow balls. The aim of this stage of the study is to obtain a correctly shaped ball using the same billet as in the previously analysed forging process. As shown in Figs. 5 and 8, it was not possible to produce correctly shaped balls from such billet if the process was carried out without the insert. It was decided that the analysis would be made for the cases in which a hollow ball was formed from the billet with the initial dimensions of $d_0 = 27$ mm and $h_0 = 30$ mm.

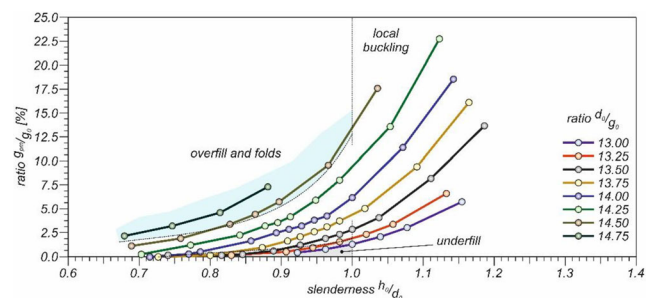


Fig. 9 Billet geometry (expressed by the slenderness ratio h_0/d_0) versus local wall thickening of a forged ball (see Fig. 4)

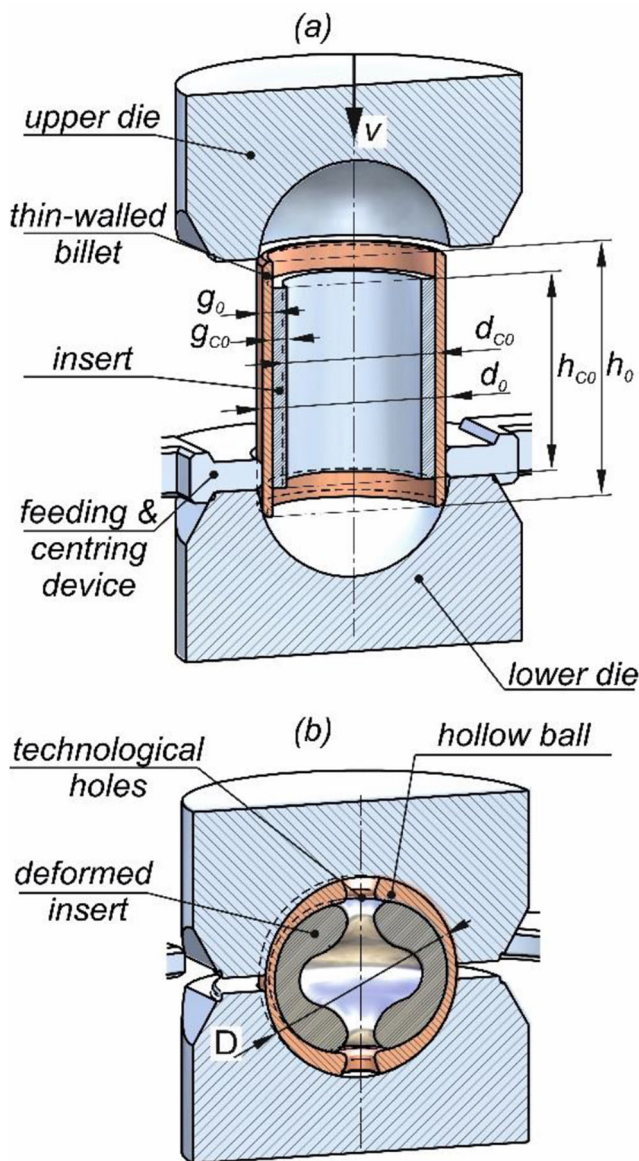


Fig. 10 Schematic design of the modified forging process for hollow balls using a plastic insert: (a) beginning of the process, (b) end of the process

A theoretical analysis of the investigated process was performed using Deform-2D/3D in the module for axisymmetric cases. The only difference between the model shown in Fig. 3 and the geometric model of the modified forging process lies in that the latter contains an additional discrete object representing the plastic insert, as shown in Fig. 11. Similarly to the billet, the insert was modelled as a rigid plastic material, and the material model of alloy BiPb25Sn12Cd12 was described by the constitutive equation:

$$\sigma_p = 109,5 \varphi^{0.042} \exp(-0.36 \varphi) \dot{\varphi}^{0.16} \exp(-0.22 \dot{\varphi} \cdot 2.6 \varphi), \quad (2)$$

where σ_p is the flow stress, φ is the effective strain and $\dot{\varphi}$ is the strain rate. This model was determined in previous studies

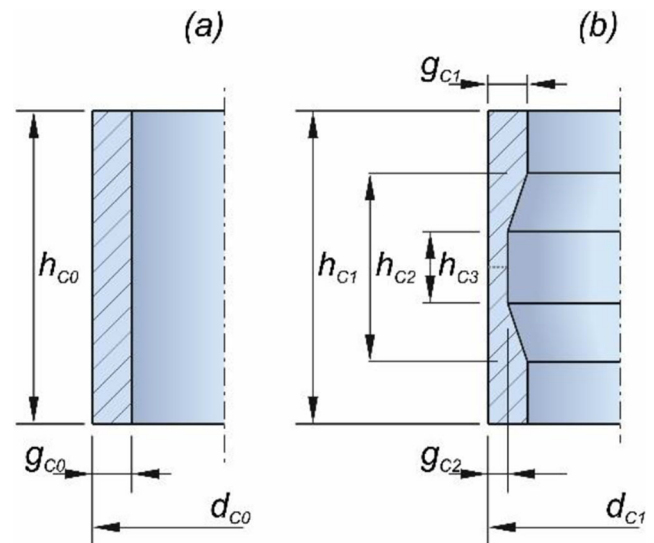


Fig. 11 Shape and defined dimensions of a plastic insert: (a) with a constant cross section, (b) with a variable cross section (description in the text)

based on the frictionless upsetting of cylindrical specimens with initial dimensions of 20 mm × 30 mm.

The conditions of contact between the billet (aluminium alloy) and the plastic insert (low melting alloy) were described by a Coulomb friction model and a coefficient of friction $\mu = 0.09$. In the simulation, it was assumed that the plastic insert was a condition-imposing object (the so-called master object). The value of the coefficient of friction was determined in a ring upsetting test performed on anvils that were made of the same material as the billet in the forging process for balls.

The experimental tests of the modified process were carried out in the same laboratory conditions as those applied in the tests of the forging process without the use of an additional plastic insert (see Subsection 3.1).

4.2 Plastic insert with a constant cross section

A numerical analysis of the forging process for hollow balls included cases in which the plastic insert had the initial height h_{C0} from 22 mm to 30 mm and the initial wall thickness g_{C0} from 2 mm to 6 mm, as shown in Fig. 11a. Given the assumption of constant dimensions of the billet ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm), in all analysed cases, the plastic insert's outside diameter d_{C0} was maintained constant at 23 mm. The tested combinations of initial dimensions of the plastic insert are listed in Table 2.

Experimental tests were carried out for selected cases in order to compare the numerical results with real conditions of forming balls. Generally, it can be claimed that the numerical results reflect the real conditions in a relatively accurate way. A comparison of the force parameters (Fig. 12) and the changes in the shape of the forged ball shows a good qualitative and quantitative agreement. Nevertheless, in the cases

Table 2 FEM-simulated combinations of initial dimensions of the plastic insert with a constant cross section, denoted as in Fig. 11a

Thickness g_{c0} , mm	Height h_{c0} , mm				
	18	22	24	26	30
2.0			X	X	X
3.0	X	X	X	X	X
4.0	X	X	X	X	X
5.0	X	X	X	X	X
6.0	X	X			

with a potential risk of buckling, the simulation indicates that the material is able to “heal” this defect, which is not entirely true as evidenced by the final shape of the balls shown in Fig. 13. These balls were obtained in the experimental tests performed using the plastic insert with a thickness g_{c0} of 2 mm and 5 mm and an initial height h_{c0} of 26 mm. The problem of interpreting results and comparing experimental and numerical findings is raised and discussed in detail later on in the paper. Now, let us move on to a discussion of the numerical results.

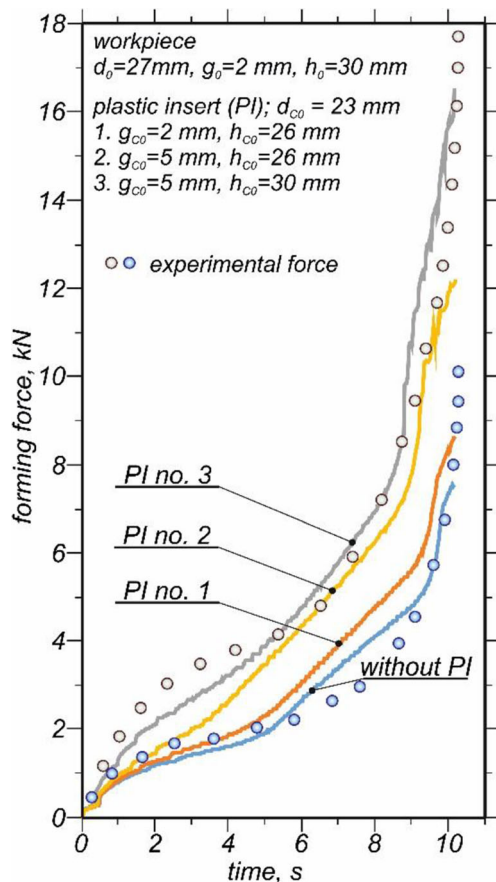
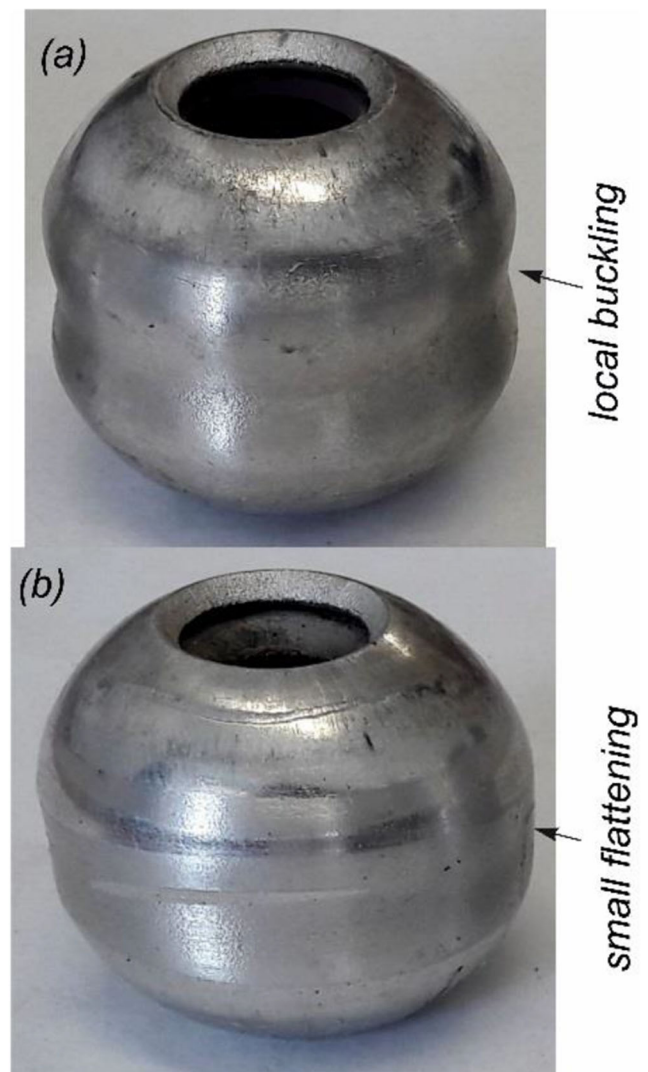
**Fig. 12** FEM-simulated forming force for selected cases of forming hollow balls using a plastic insert; the numerical results are compared with the FEM results of the forging process performed without an insert and experimental results

Figure 14 shows the changes in the shape of a ball with a plastic insert with the initial dimensions $d_{c0} = 23$ mm, $g_{c0} = 2$ mm and $h_{c0} = 26$ mm. The wall thickness of the insert was identical to that of the billet, while the insert's height was 87% of the height of the billet. The results demonstrate that the plastic insert with such a small relative wall thickness has an insignificant effect on the forging process conditions. At an early stage of the forming process, both the workpiece and the insert undergo local compression, and as a result, the contact surface between the insert and the workpiece is reduced to a small area that is denoted as detail A in Fig. 14a. With further upsetting of the workpiece and the insert, a growing gap is created between the inside wall of the workpiece and the outer surface of the insert (it is marked in Fig. 14 as detail B and detail D). Although the contact between the insert and the workpiece is increased with time (detail A in Fig. 14d), the

**Fig. 13** Final shape of the experimental ball formed from a billet with the initial dimensions $d_0 = 27$ mm, $g_0 = 2$ mm and $h_0 = 30$ mm using a plastic insert with a constant cross section and the dimensions $d_{c0} = 23$ mm, $h_{c0} = 26$ mm and g_{c0} of 2 mm (a) and 5 mm (b), respectively

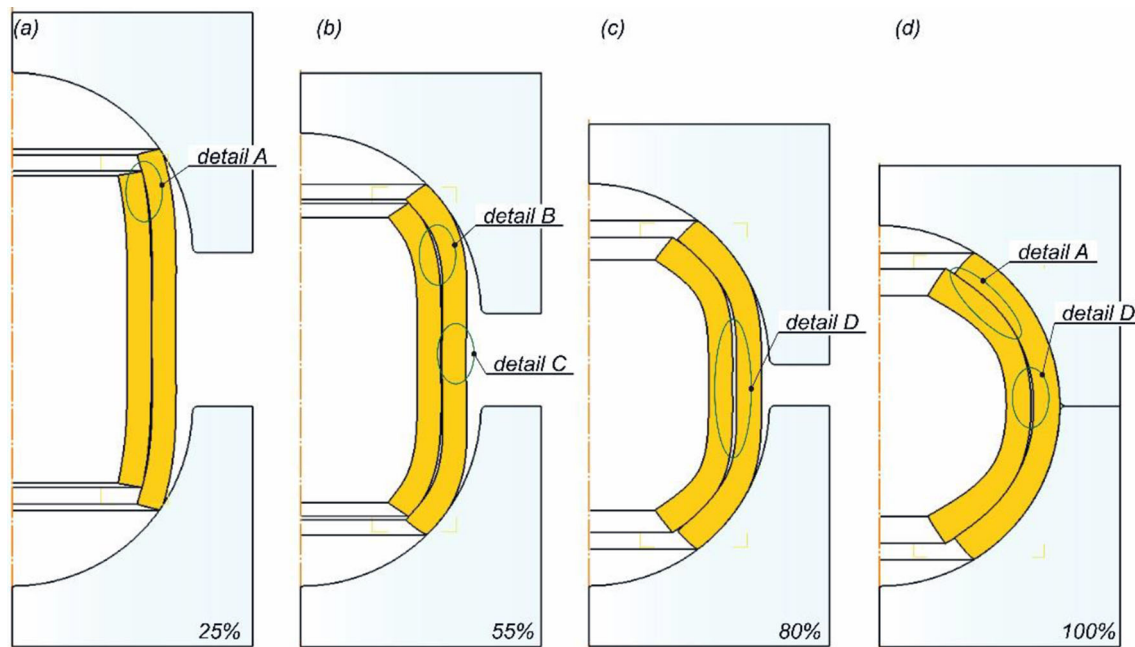


Fig. 14 Changes in the shape of a workpiece ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm) and a plastic insert ($d_{C0} = 23$ mm, $g_{C0} = 2$ mm, $h_{C0} = 26$ mm); description in the text

lack of the insert's impact on the central region of the workpiece (detail C in Fig. 14b) causes a collapse of the workpiece wall, which consequently, leads to buckling. Therefore, the set objective is not attained. Hence, the shape of the balls obtained at a later stage of the process should be considered incorrect, because given the previously observed collapse of the workpiece wall shown in Fig. 13a, it can be claimed that the forging process for this case will fail.

One could ask what will happen if the thickness of the plastic insert is increased e.g. to $g_{C0} = 5$ mm. The answer to this question is given in Fig. 15. In general, the forming conditions have not improved significantly. Previously observed phenomena still occur. At an early stage of the forging process, the workpiece and the insert are compressed, which gives rise to local contact between these objects (detail A in Fig. 15a). Further upsetting results in the formation of a significant gap between the workpiece and the insert (detail B in Fig. 15b). When the insert with a bigger wall thickness g_{C0} is used, an additional contact area occurs with time; this area is marked as detail D in the figure. This contact, however, is momentary and does not play a significant role in the forging process. An analysis of the data in Fig. 13b reveals that the increase in the insert wall thickness has improved the forging quality; however, the improvement is not considerable enough to regard the quality of the ball as satisfactory. It can therefore be claimed that the assumed objective has not been accomplished in this case either.

A detailed comparison of the impact of the plastic insert wall thickness on the changes in the outer surface of the ball profile is given in Fig. 16. Before moving into the discussion, it should be briefly explained how to read the plots in the

figure. The data in Fig. 16a demonstrate that as the forging process continues, at some point, the workpiece wall profile undergoes a collapse if no plastic insert is used. A detailed analysis of the results allows us to conclude that if such collapse is observed when the process progress is between 45% and 60%, then buckling is bound to occur. Even though the workpiece wall profile in a later stage of the simulation (79% and 100%, as shown in Fig. 16a) is convex, this observation cannot be used as a sole rationale for deciding whether the forging process is stable or not. It can also be assumed that if we track the history of changes in the shape of a ball profile and show that the line of this profile becomes non-convex at any moment (e.g., the derivative of this line assumes a negative sign at the point for the coordinate $H/2 = 0$ mm), this would mean that the forging conditions are no longer stable and buckling will occur, as observed in the experiment (Fig. 13a). A different measure of the degree of non-convexity of this line is the $\Delta_{\max}$ parameter (Fig. 16b), i.e., the difference between the furthest point on the profile line (in the direction of the R coordinate) and the midpoint located on the above-mentioned line at the height coordinate $H/2 = 0$ mm.

An analysis of the plot shown in Fig. 16b reveals that a change in the wall thickness of the plastic insert does not make the contour line of the ball profile convex. This means that the use of the plastic insert with a constant cross section does not make it possible to attain the set objective, i.e., ensuring stable conditions of the analysed forging process for hollow balls. This is evidenced by the increase in the $\Delta_{\max}$ parameter with increasing the plastic insert thickness (Fig. 16b). Obtained values of this parameter are listed in Table 3.

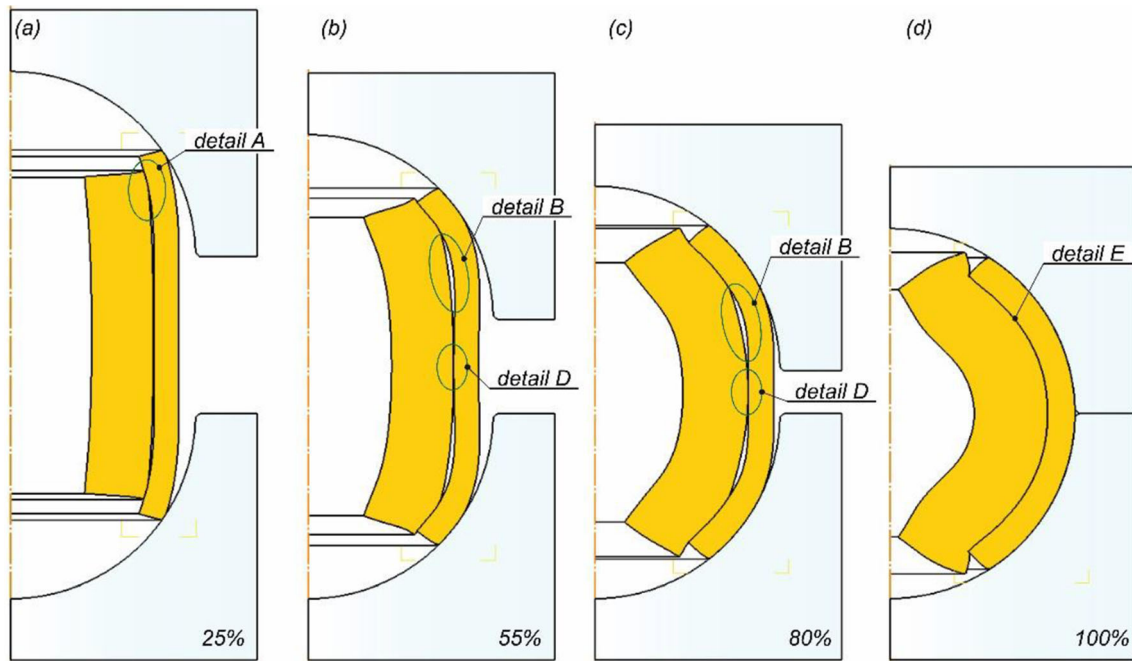


Fig. 15 Changes in the shape of a workpiece ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm) and a plastic insert ($d_{C0} = 23$ mm, $g_{C0} = 5$ mm, $h_{C0} = 26$ mm); description in the text

Analysing the changes in the shape of the workpiece and plastic insert shown in Figs. 17 and 18, one can come to a conclusion that even by changing the plastic insert height, one cannot be sure that the set objective will be accomplished. Moreover, a reduction in height practically eliminates any positive effect of the insert on the forging process, as evidenced by the details B, C and D in Fig. 17 (the letters correspond to the denotations in Figs. 14 and 15). On the other hand, an increase in the wall thickness of the insert causes filling of insert material in the space inside the workpiece, which leads to an unnecessary increase in the forming force (even by two times, see Fig. 12) and obstructs the deformation

of the workpiece, enhancing the effect of workpiece wall collapse (detail C in Fig. 17). The end result is a ball with a lower final height h_K as well as a potential risk of flash formation (detail F in Fig. 18). Given the possible occurrence of buckling, overlap may occur, too.

4.3 Plastic insert with a variable cross section

A further analysis of the investigated forging process for hollow balls concerned cases in which a plastic insert with a variable cross section was used (Fig. 11b). This analysis was divided into two stages. First, a comprehensive analysis was

Fig. 16 Changes in the outer profile of the workpiece (billet dimensions: $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm) in the forging process performed without a plastic insert (a) and with a plastic insert (b) when the process progress is 60% (b) versus the plastic insert wall thickness (insert dimensions are constant: $d_{C0} = 23$ mm, $h_{C0} = 26$ mm); description in the text

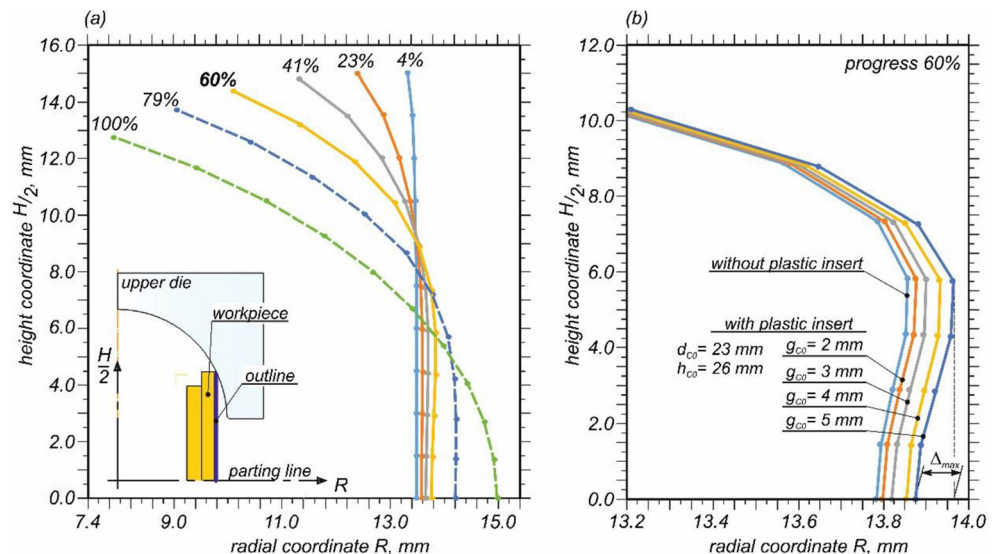


Table 3 Values of the $\Delta_{\max}$ parameter calculated for the forging cases shown in Fig. 16b

	Without insert	Plastic insert thickness g_{C0} , mm			
		2.0	3.0	4.0	5.0
$\Delta_{\max}$, mm	0.0747	0.0793	0.0800	0.0871	0.0892

performed for a wide range of values of the geometric parameters of the insert. Next, the range of the tested parameters was narrowed to a region in which the forging process is the most effective. This region was selected on the basis of the results obtained in the first part of the study. Referring to the considerations discussed in previous chapters, the following assumptions were made in the first stage of the analysis:

- In the analysed forging process, a hollow ball is formed from a billet with the following dimensions (Fig. 10a): $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm.
- The geometry of the plastic insert (Fig. 11b) is described by constant and variable parameters.
- The constant parameters are the total insert height $h_{c1} = 26$ mm (referring to the parameter h_{c0} of the plastic insert with a constant cross section discussed in the previous section of the paper) and the outside diameter $d_{c1} = 23$ mm (resulting from the billet's dimensions).
- The variable parameters are (Fig. 11b) the insert thickness g_{c1} (taken in the range from 2.0 to 6.0 mm), the necking thickness g_{c2} (its value is taken in the range from 0.5 to

2.5 mm depending on the thickness g_{c1}), the height h_{c2} (taken in the range from 8.0 to 12.0 mm), and the necking height h_{c3} (its value is taken in the range from 1.0 to 5.0 mm depending on h_{c2}).

First of all, the conditions of the forging process for hollow balls in question were assessed. To this end, the history of changes in the workpiece outer profile was examined and the effect of using a plastic insert of specific dimensions was investigated. For a quantitative assessment of the results, and thus for establishing a criterion for the attainment of the set objective, two parameters were adopted: the $\Delta_{\max}$ parameter, which was previously defined in Fig. 16b, and the forging height h_K (Fig. 4). The values of these parameters, depending on the dimensions of the plastic insert with a variable cross section (Fig. 11b) are shown in Figs. 19 and 20, respectively.

It was observed that the relative size of the plastic insert wall necking in its central region significantly affects the ball forming conditions. A reduction in the thickness ratio g_{c2}/g_{c1} leads to a significant improvement in the forging conditions, as evidenced by the fact that the $\Delta_{\max}$ parameter can be lower than 0.02 mm. At the same time, however, an analysis of the results given in Fig. 19b demonstrates that this relationship has its extreme values, i.e., it is possible to indicate optimal dimensions of the necking. The same conclusion can be reached by taking into account the other two dimensions, i.e., the heights h_{c2} and h_{c1} .

However, in order to be able to fully define the optimal dimensions of the plastic insert, one must additionally analyse the other parameter describing the insert, i.e., the expected

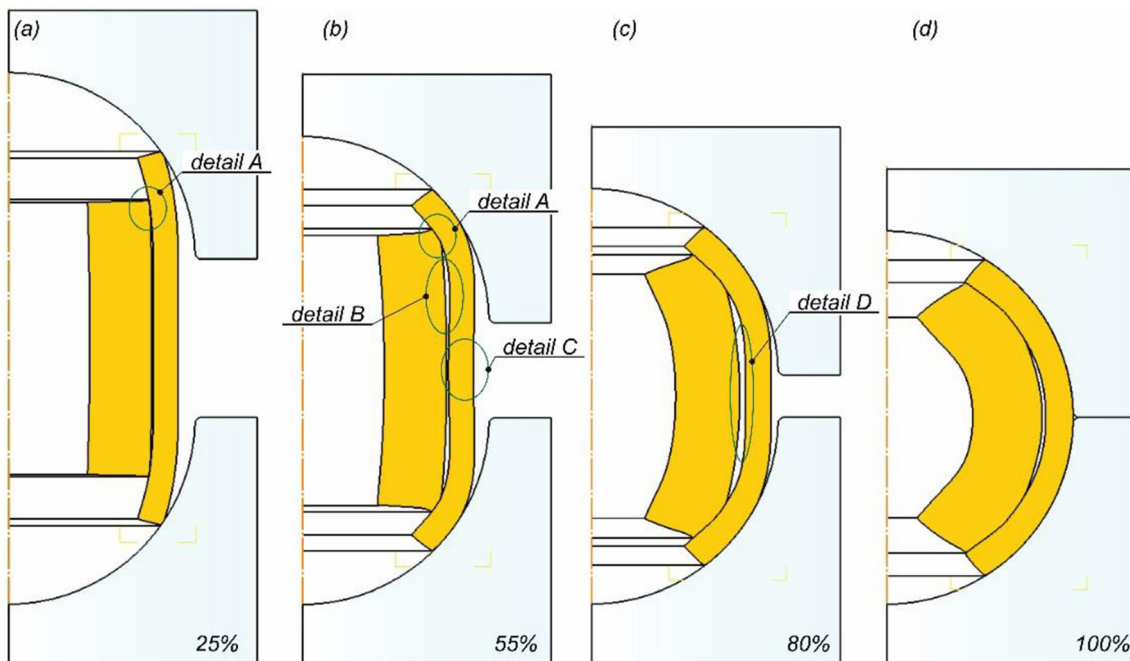


Fig. 17 Changes in the shape of a workpiece ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm) and a plastic insert ($d_{C0} = 23$ mm, $g_{C0} = 5$ mm, $h_{C0} = 22$ mm); description in the text

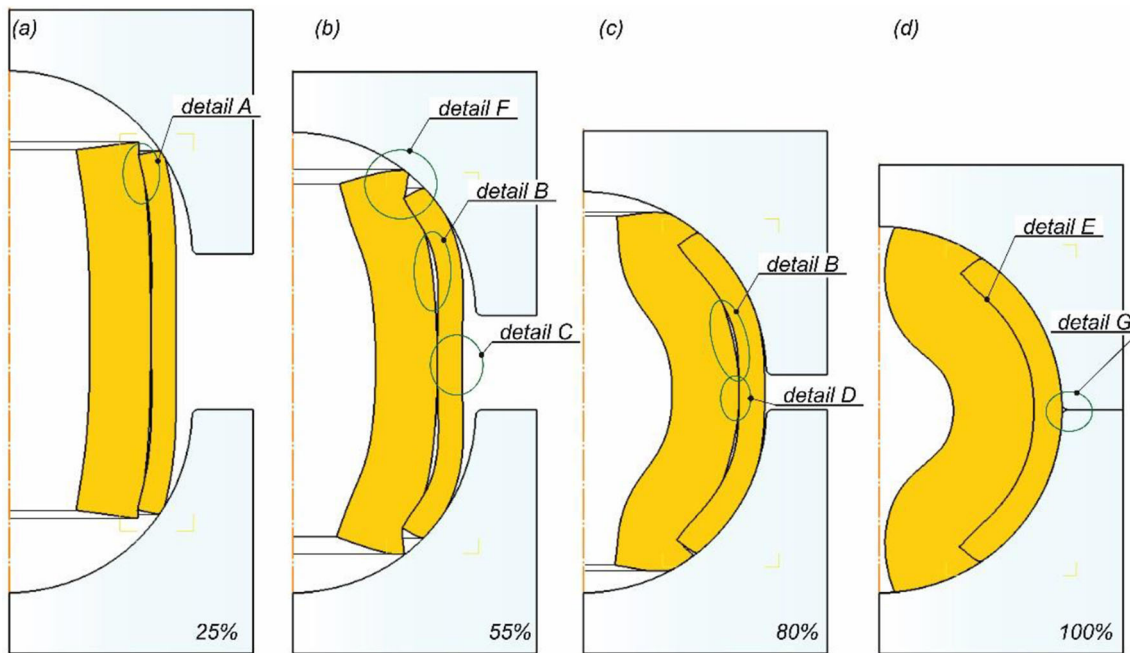


Fig. 18 Changes in the shape of a workpiece ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm) and a plastic insert ($d_{C0} = 23$ mm, $g_{C0} = 5$ mm, $h_{C0} = 30$ mm); description in the text

height of the forging, h_C (Fig. 20). It turns out that obtaining a ball with the highest possible height is possible when we use the plastic insert with higher values of the aforementioned thickness ratio g_{C2}/g_{C1} . In addition, the application of a higher value of the necking height h_{C1} ensures that the difference between results will be lower. The final analysis based on polyoptimization, where the objective function is to obtain the smallest possible value of the parameter $\Delta_{\max}$ and the largest possible forging height h_K in the tested range of the variable parameters, which can be written using the equation:

$$\Phi_{\text{target}} = \min \left[\left(\frac{\Delta_{\max} - \Delta_{\max(\min)}}{\Delta_{\max(\max)} - \Delta_{\max(\min)}} \right) + \left(\frac{h_{K(\max)} - h_K}{h_{K(\max)} - h_{K(\min)}} \right) \right], \quad (3)$$

which indicates that the optimal forging conditions are ensured when the plastic insert has the following dimensions: $h_{C2} = 10$ mm, $h_{C3} = 3$ mm, $g_{C1} = 5$ mm and $g_{C2} = 0.75$ mm. Figure 21 shows successive stages of the forging process performed with the use of such insert. The figure also shows the vectors of material flow velocity, which provides a deep insight into the problem.

From an early stage of the forging process, one can observe three regions of contact between the plastic insert and the inner surface of the workpiece wall; these regions are marked in Fig. 21 as details A and B. Despite the occurrence of a significant void between the insert and the workpiece (detail C in Fig. 21), the forging conditions can be considered stable. The stability of the forging process predominantly depends on

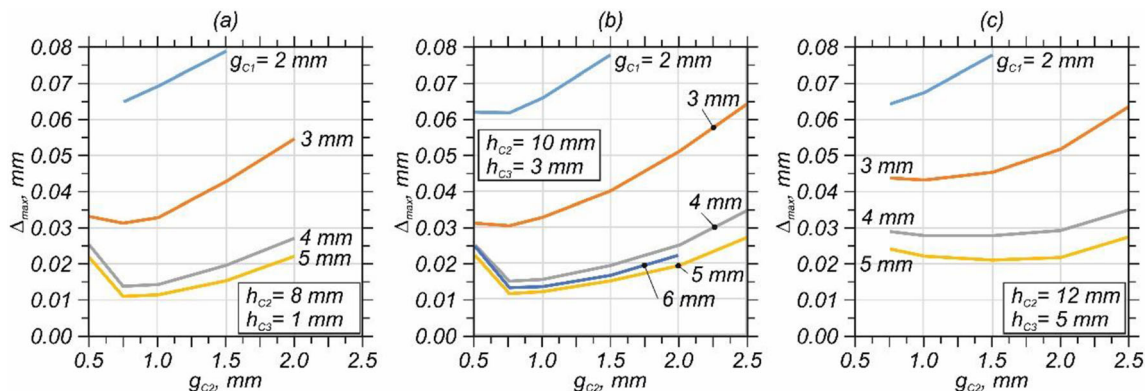


Fig. 19 Values of the $\Delta_{\max}$ parameter calculated for the forging process (billet dimensions: $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 27$ mm) performed using a plastic insert of varying dimensions, as shown in Fig. 11b; description in the text

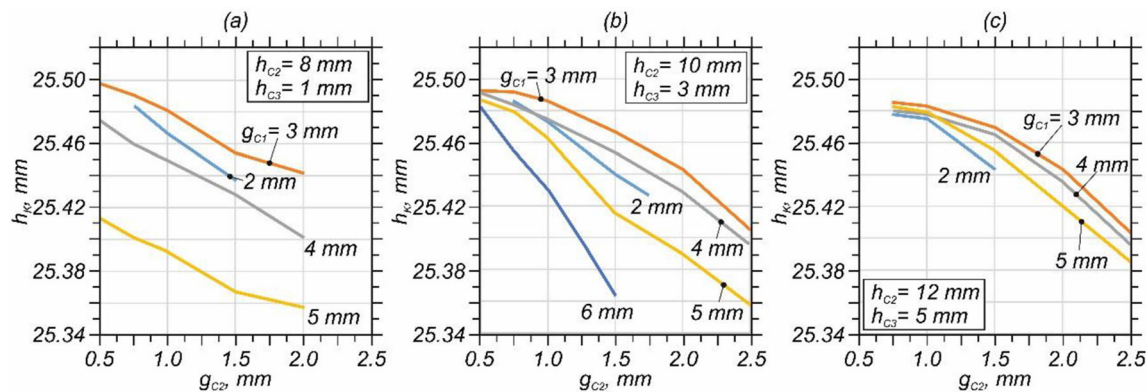


Fig. 20 Forging height h_K calculated for the forging process (billet dimensions: $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 27$ mm) performed using a plastic insert of varying dimensions, as shown in Fig. 11b; description in the text

the way in which the insert is deformed in its centre (detail B in Fig. 21). A collapse that occurs in this area of the insert (detail D in Fig. 21) exerts a strong impact on the workpiece wall, pushing the workpiece wall in the radial direction, as evidenced by the material flow velocity. In effect, the buckling of the workpiece wall is prevented. It can therefore be concluded that the set objective has been attained and the proposed shape of the plastic insert meets the requirements.

The positive results obtained in the first stage of the study encouraged the authors to undertake further analyses. In the second stage, it is assumed that the insert necking dimensions g_{C1} , g_{C2} and h_{C3} are constant and their values were calculated based on the results obtained in the first stage of the analysis. In contrast, the heights h_{C1} and h_{C2} are variable parameters. Such assumption makes it possible to investigate the impact of

all dimensions of the plastic insert with a variable cross section on the forming conditions and, consequently, to determine optimal values of these dimensions.

Figure 22 shows the effect of changing the plastic insert's heights h_{C1} and h_{C2} (for the constant values of the thicknesses $g_{C1} = 5$ mm and $g_{C2} = 0.75$ mm and the necking height $h_{C1} = 3$ mm, according to Fig. 11b) on the value of the parameter $\Delta_{\max}$. An increase in the total height h_{C1} of the insert leads to higher stability of the forging conditions. The value of the height h_{C1} is very close to the billet height h_0 (in this case, it is 30 mm), and the outer surface of the ball profile can basically be considered convex, which means that no buckling will occur. When the height h_{C1} is at least 28 mm (which is about 90% of the height of the billet), the parameter $\Delta_{\max}$ is below 0.02 mm; the best result is achieved for the height $h_{C1} =$

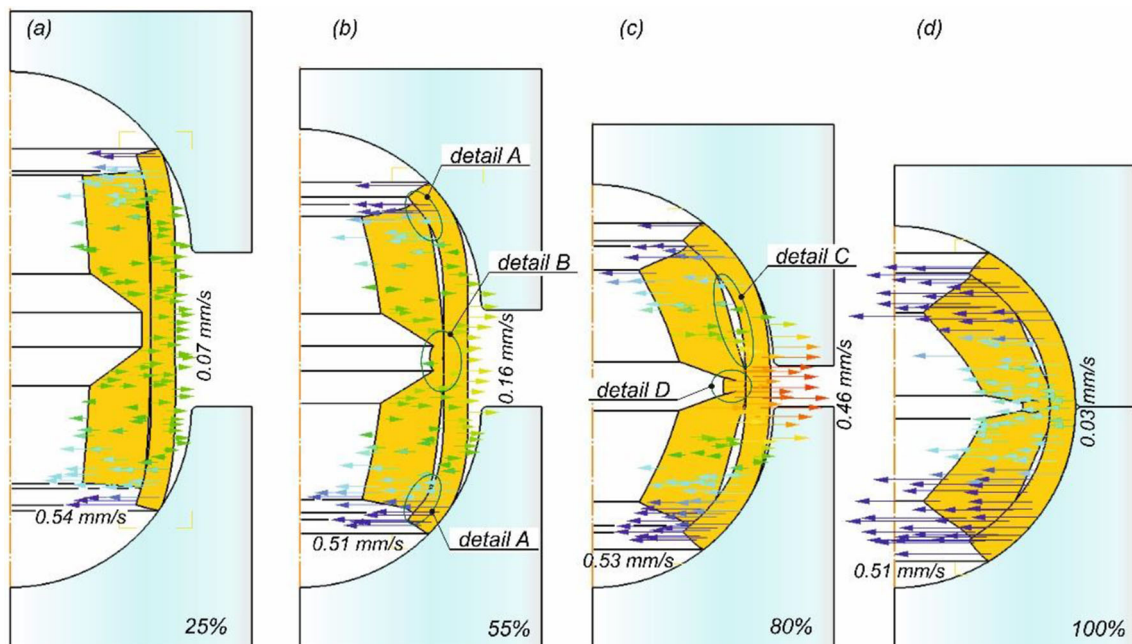


Fig. 21 Changes in the shape of a workpiece ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 26$ mm) in the forging process performed with a plastic insert with the dimensions $d_{C1} = 23$ mm, $g_{C1} = 5$ mm, $g_{C2} = 0.75$ mm, $h_{C1} = 26$ mm, $h_{C2} = 10$ mm, $h_{C3} = 3$ mm and the vectors of material flow; description in the text

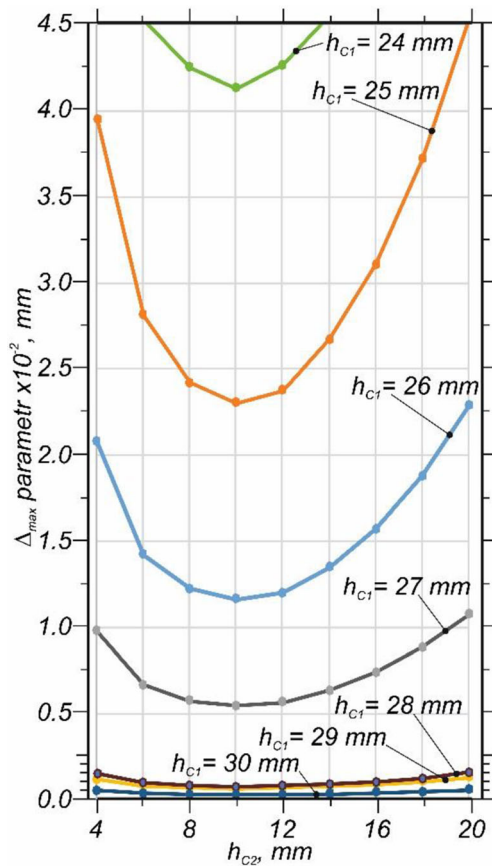


Fig. 22 Parameter $\Delta_{\max}$ calculated for the forging process (billet dimensions: $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 27$ mm) performed using a plastic insert with variable necking, as shown in Fig. 9b, the constant dimensions being $h_{c3} = 3$ mm, $g_{c1} = 5$ mm and $g_{c2} = 0.75$ mm; description in the text

30 mm when $\Delta_{\max} = 0.003$ mm. A comparison of these values with the data listed in Table 3 reveals that the use of the plastic insert with a variable cross section ensures stable forging conditions. However, the dependence of the parameter $\Delta_{\max}$ on the height h_{c2} is parabolic, with a clear extreme value. The parameter $\Delta_{\max}$ reaches the lowest values when the height h_{c2} is approximately 10 mm.

In addition to the parameter $\Delta_{\max}$, the workpiece height h_K (Fig. 4) was also taken into consideration in the analysis. The results demonstrate that an increase in the height h_{c1} has a negative effect on the workpiece height h_K . The forming conditions resemble those observed in the previous case shown in Fig. 18. Namely, due to the fact that the height of the insert in the workpiece is too high, the material of the insert fills the space above the workpiece, preventing the flow of the workpiece material in the axial direction. The effect of changing the insert dimensions is plotted in Fig. 23, where it is shown that the change in the height h_{c1} has a more significant effect than the change in the height h_{c2} . By taking into account the variables and analysis results shown in Figs. 22 and 23, in combination with parameter polyoptimization based on the

objective function Φ_{target} in accordance with Equation (3), it is confirmed that the previously determined dimensions of the plastic insert $h_{c1} = 26$ mm, $h_{c2} = 10$ mm, $h_{c3} = 3$ mm, $g_{c1} = 5$ mm and $g_{c2} = 0.75$ mm, are optimal when a hollow ball is forged from a billet with the dimensions $h_0 = 30$ mm and $d_0 = 27$ mm.

The numerical results were verified by experimental tests involving the formation of a hollow ball from a tube with the same dimensions as in the numerical analysis (i.e., $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 30$ mm). The forging process was performed with the use of the plastic insert (Fig. 11b) with a constant outside diameter $d_{c1} = 23$ mm and constant dimensions of the necking $h_{c2} = 10$ mm, $h_{c3} = 3$ mm and $g_{c3} = 1$ mm. The tests were performed using two heights h_{c1} (28 mm and 30 mm) and two thicknesses g_{c1} (4 mm and 5 mm). It should be clarified that some of these dimensions slightly differ from the optimal values that were determined in the theoretical analysis. The use of an insert with its thickness g_{c1} below 1 mm is pointless due to the difficulty of ensuring sufficiently high tolerance. The value of the height h_{c1} was selected deliberately due to practical reasons.

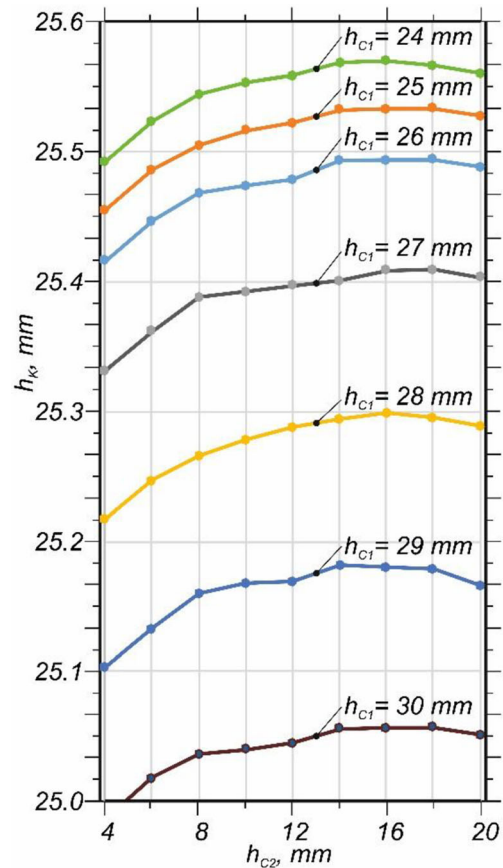


Fig. 23 Forging height h_K calculated for the forging process (billet dimensions: $d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 27$ mm) performed using a plastic insert with variable necking, as shown in Fig. 11b, the constant dimensions being $h_{c3} = 3$ mm, $g_{c1} = 5$ mm and $g_{c2} = 0.75$ mm; description in the text

Examples of hollow balls obtained in the experimental tests are shown in Fig. 24. The top photographs show the view from the side of the top die, while the photographs in the bottom, from the side of the bottom die. All cases considered in the experiments were successful. The balls have the correct outer profile and are free from any shape defects. The experimental height h_K of the forged balls (Figs. 4 and 24) shows high agreement with the numerical results.

Additionally, Fig. 25 shows the axial section of a hollow ball obtained in two analysed cases with two different insert thicknesses g_{C1} . The experimental results show agreement with the theoretical findings. The application of the plastic insert with a variable cross section is effective, as evidenced by detail A in Fig. 25. During the forming process, the insert exerts in the marked area the required load ensuring stable forming conditions, ultimately resulting in the production of a ball with the correct shape and relatively constant wall thickness. In addition, the void marked in Fig. 25 as detail B is identical to that obtained in the numerical analysis and has no negative impact on the final result. The only deviation from the theoretical results occurs in the area marked as detail C. This can be explained by the fact that during the forming process, the insert is slightly displaced towards the bottom die. As a result, the diameter of the hole in the lower area of the ball (i.e., from the side of the bottom die) is larger than the

hole in the upper area. This difference ranges from 1 mm to 3 mm approximately, depending on the insert height h_{C1} .

5 Summary and conclusions

This paper presented the results of a study investigating the cold forging process for hollow aluminium alloy balls with an outside diameter of 30 mm. The primary objective of the study was to obtain balls with the required shape and the maximum height and, at the same time, to ensure the most stable forming conditions. The study was divided into three stages. The preliminary tests have demonstrated that the formation of balls from a billet with merely a 2-mm wall thickness is a very difficult task due to the occurrence of buckling, which considerably limits the range of permissible values of other dimensions of the billet, i.e., height and outside diameter. This, in turn, makes it impossible to obtain balls with the required shape and dimensions. The authors have solved this technological problem by introducing an additional tool that would have a positive effect on the inner surface of the workpiece and thus would ensure stable forming conditions and the attainment of the set objective. The authors proposed that this tool was a plastic insert, i.e., an additional flexible core that could easily be removed from the forged ball after the forming

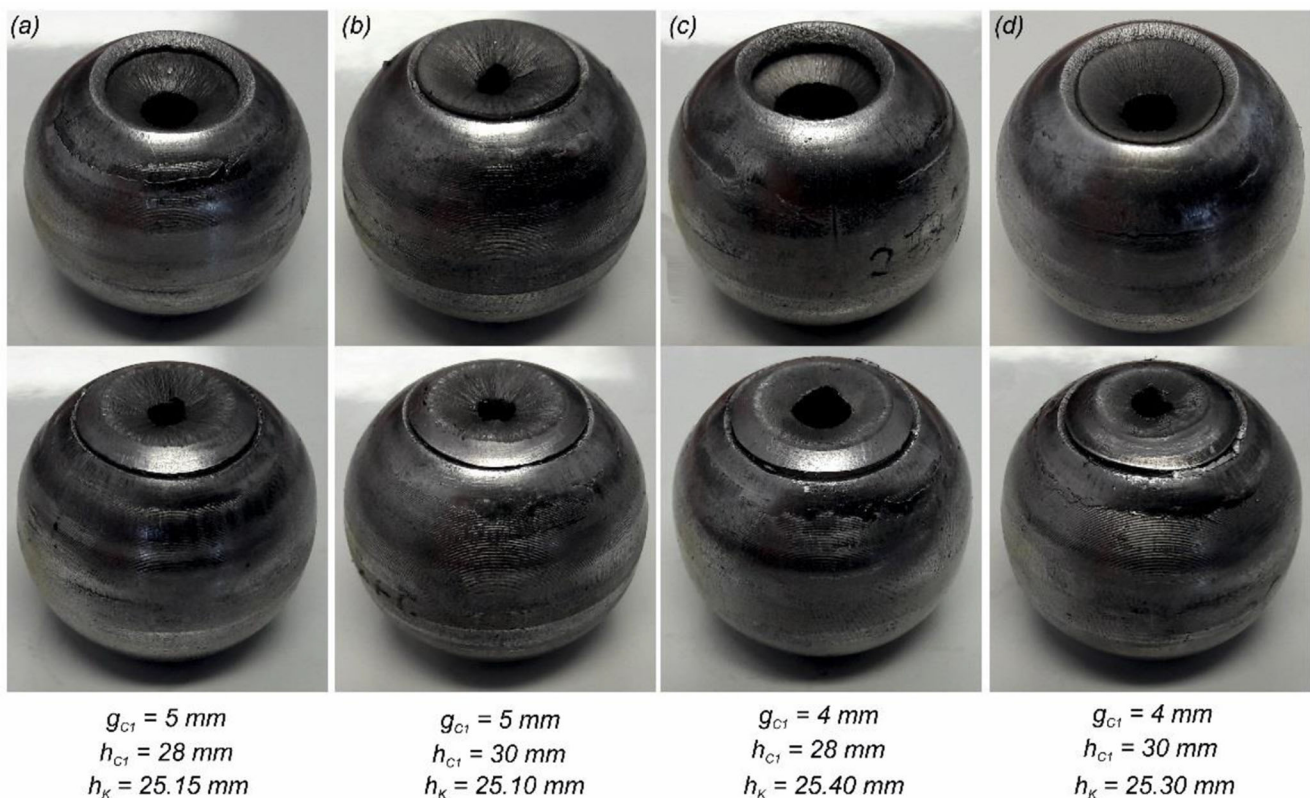


Fig. 24 Examples of hollow balls formed from a tube ($d_0 = 27 \text{ mm}$, $g_0 = 2 \text{ mm}$, $h_0 = 27 \text{ mm}$) in a forging process using a plastic insert (as in Fig. 11b) with the dimensions $h_{C2} = 10 \text{ mm}$, $h_{C3} = 3 \text{ mm}$, $g_{C3} = 1 \text{ mm}$ and g_{C1} and h_{C1} given in the figure; description in the text

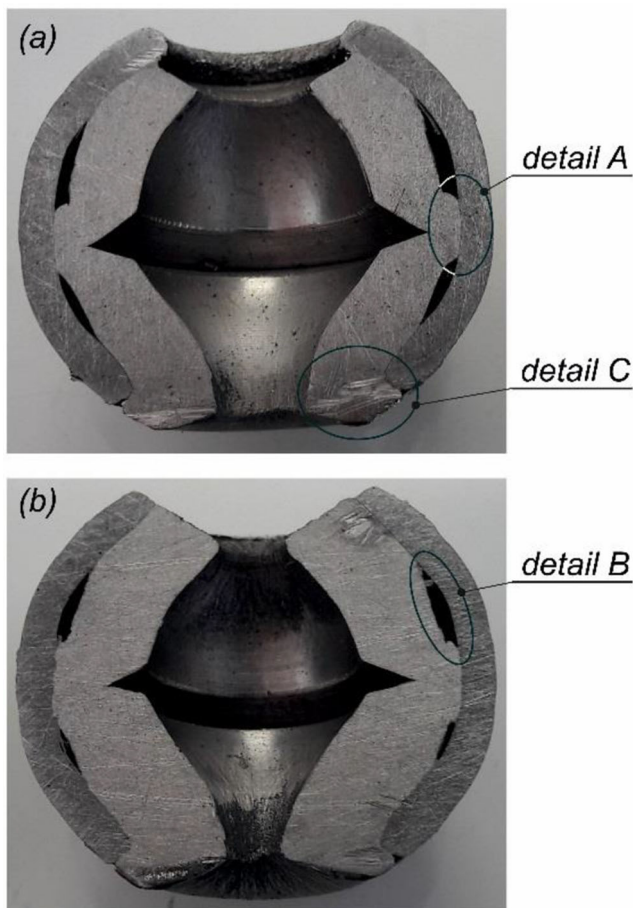


Fig. 25 Axial section of a hollow ball formed from a tube ($d_0 = 27$ mm, $g_0 = 2$ mm, $h_0 = 27$ mm) in a forging process performed using a plastic insert (as in Fig. 11b) with the dimensions $h_{C1} = 28$ mm, $h_{C2} = 10$ mm, $h_{C3} = 3$ mm, $g_{C3} = 1$ mm and $g_{C1} = 4$ mm (a) and 5 mm (b); description in the text

process. A low melting alloy based on lead and bismuth was selected to this end; the alloy had a melting point below the boiling point of water and plastometric characteristics similar to those of technically pure lead. The research on the determination of optimal shape of the insert was divided into two stages. Ultimately, the optimal shape and dimensions of the plastic insert were determined. The study has demonstrated that the proposed solution of using a plastic insert in the forging process for hollow balls is effective and promising. The results of the study lead to the following conclusions:

- The use of a lead-based low melting alloy in the cold forging process for hollow parts made of aluminium alloy generally leads to improved forming conditions.
- The optimal shape of the plastic insert prevents the buckling of a workpiece wall.
- The use of the plastic insert with optimal shape and dimensions ensures both the improvement in general forming conditions and the production of balls with the required shape and dimensions.



Fig. 26 Examples of finished products obtained from hollow balls with the use of a chuck (shown in the photograph) and a CNC lathe

Finally, the authors would like to show an example of finishing of the outer surface of obtained hollow balls. Figure 26 shows the finished products and an example of the chuck. The finishing of the balls shown in the photograph was done using a CNC lathe.

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References

1. Bartnicki J, Magryta J, Pater Z, Samołyk G (2010) Rotary compression processes of hollowed parts. *Steel Res Int* 81(9):206–209
2. Tomczak J, Pater Z, Bulzak T (2017) A theoretical and experimental analysis of rotary compression of hollow forging formed over a mandrel. *Strength Mater* 49(4):555–564
3. Tomczak J, Pater Z, Bulzak T (2016) The influence of hollow billet thickness in rotary compression. *Int J Adv Manuf Technol* 82(5–8): 1281–1291
4. Samołyk G (2018) Numerical analysis of a forging process for producing a hollow ball from tube. *Adv Sci Technol Res J* 12(3): 150–157
5. Samołyk G (2014) Numerical investigation of producing a Ti6Al4V alloy jaw coupling sleeve-disk by orbital forging. *Metalurgija* 53(4):497–500
6. Winiarski G, Gontarz A, Dziubińska A (2017) The influence of tool geometry on the course of flanges radial extrusion in hollow parts. *Arch Civ Mech Eng* 17(4):986–996

7. Tomczak J, Bulzak T, Pater Z (2016) Theoretical and experimental analysis of rotary compression of ball pins hollow forgings. *Adv Sci Technol Res J* 10(32):109–117
8. Skrochocki D, Tomczak J (2016) Numerical simulation of rotary compression process of hollow balls. *Strength Mater* 48(4):583–591
9. Han F, Wang Y, Wang Z (2018) Mechanical bending property of ultra-high strength steel sheets in roll forming process. *Int J Precis Eng Manuf* 19(12):1885–1893
10. Alzahrani B, Ngaile G (2016) Preliminary investigation of the process capabilities of hydroforging. *Materials* 9(40):1–13
11. Krakowski M, Bartnicki J (2015) Analysis of rubber forming process of fire barrier from titanium CP2 alloy for AW 139 helicopter. *Adv Sci Technol Res J* 9(26):66–71
12. Qin Y, Ma Y, Balendra R (2004) Pressurising materials and process design considerations of the pressure-assisted injection forging of thick-walled tubular components. *J Mater Process Technol* 150:30–39
13. Winiarski G (2013) Theoretical analysis of the forging process for producing hollow balls. *Adv Sci Technol Res J* 7(18):68–73
14. Chavdar B, Goldstein R, Yang X, Butkovich J, Ferguson L (2015) Hot hydroforging for lightweighting. IDE 2015; Bremen, Germany; Sep. 23–25, Vol. 5, 117–128 (in [Fluxreol.com/Library/Papers](https://www.fluxreol.com/Library/Papers))
15. Chavdar B, Goldstein R, Ferguson L (2016) Hot hydroforging for lightweight bimaterial gears and hollow products. 23rd IFHTSE Congress; Savannah, GA - USA; April 18–22 (in [Fluxreol.com/Library/Papers](https://www.fluxreol.com/Library/Papers))
16. Tekkaya A, Khalifa NB, Grzanic G, Hölker R (2014) Forming of lightweight metal components: need for new technologies. *Procedia Eng* 81:28–37
17. Ma Y, Qin Y, Balendra R (2005) Forming of hollow gear-shafts with pressure-assisted injection forging (PAIF). *J Mater Process Technol* 167:294–301
18. Goldstein R, Chavdar B, Ferguson L (2016) Modeling of the heating sequences of lightweight steel/aluminum bimaterial billets for hot forging and hot hydroforging. 23rd IFHTSE Congress; Savannah, GA - USA; April 18–22 (in [Fluxreol.com/Library/Papers](https://www.fluxreol.com/Library/Papers))
19. Wu P, Wang B, Lin J, Zuo B, Li Z, Zhou J (2018) Investigation on metal flow and forming load of bi-metal gear hot forging process. *Int J Adv Manuf Technol* 88:2835–2847
20. Politis DJ, Lin J, Dean TA, Balint DS (2014) An investigation into forging of bi-metal gears. *J Mater Process Technol* 214(11):2248–2260
21. Graf M, Härtel S, Binotsch C, Awiszus B (2017) Forging of lightweight hybrid metallic-plastic components. *Procedia Eng* 184:497–505
22. Alhussainy F, Sheikh M, Hadi M (2017) Behaviour of small diameter steel tubes under axial compression. *Structures* 11:155–163
23. Matveev A, Truskov A, Drapkin J (2004) Method of manufacturing hollow spherical parts. RU Patent 2242315C2
24. Sokolov A, Surygin A, Mishutin A (2002) Method for manufacture of spherical articles. RU Patent 2238816C2
25. Wang T, Zha J, Jia Q, Chen Y (2016) Application of low-melting alloy in the fixture for machining aeronautical thin-walled component. *Int J Adv Manuf Technol* 87:2797–2807
26. Wang L, Li M, Zhao L, Guo Y (2018) Research on a wrinkle-free forming method using low-melting alloy for sheet metal. *Int J Adv Manuf Technol* 99(9–12):3065–3075
27. Samolyk G, Winiarski G (2019) Analysis of single-operation cold forging of a hollow ball from a tubular billet. *Int J Adv Manuf Technol* 103(5–8):3045–3056
28. Wierzbicki Ł (2014) Strength properties of the low-melting-point alloys. *J Achiev Mater Manuf Eng* 67(1):26–31
29. Roshan MAK, Abhilash C, Prathik P, Prasanna HS (2019) Low melting point alloys: a review. *Int J Eng Res Technol* 8(4):73–75
30. Zhou J, Sun Y, Xue F (2005) Properties of low melting point Sn-Zn-Bi solders. *J Alloys Compd* 397(1–2):260–264

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