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NUMERICAL ANALYSIS OF A ROLLING PROCESS FOR PRODUCING STEEL BALLS USING HELICAL ROLLS

This paper presents the research results of the balls rolling process according to the conventional and modified methods of rolling. Theoretical analysis was carried out by using numerical methods based on the Finite Element Method. The Simufact package version 10.0 were used for calculation. Simulations of balls rolling were carried out under conditions of 3D state of strain, taking into account the effect of thermal conditions occurring during forming. The study of the achieved results showed that the best rolling process parameters were obtained for the modified method, in which the feed material is heated up to 1150 °C. In this case, the rolling parameters such as: rolling force and torque as well as tool wear reached the smallest values.

Keywords: helical rolling, FEM analysis, balls, effective strain

1. Introduction

Balls can be produced by three methods: casting, forging and rolling. Casting is one of the oldest production methods and it consists in shaping metal parts for further processing. In this manufacturing process, objects are produced by solidifying molten metal in a mold. Casting is used when the application of other techniques would be too expensive [1]. In one Polish forge, balls are produced from bars made of St90PA with increased carbon and manganese content by the die forging method. In the production cycle, balls are subjected to special heat treatment, which ensures their excellent mechanical properties, including high hardness and resistance to abrasion and cracking [2].

In the specialist literature, one can find studies on the numerical modeling of rotary piercing processes. The first attempts were made in the 1990s and were based on two-dimensional FEM models [3]. However, given the nature of metal flow, these processes should be simulated in a three-dimensional state of strain. In recent years, the three-dimensional modeling of rotary piercing was investigated by Pietisch and Thieren [4], Ceretti et al. [5] and Komori [6]. Nonetheless, the numerical models developed by the above authors are based on numerous simplifications; for instance, they do not take into account thermal phenomena occurring in the metal being formed [4-6], or they are limited to either the steady-state [6] or outset of the process [4, 5]. Given the above shortcomings, the researchers from the Lublin University of Technology attempted to model a complete piercing process in skew rolls, with the investigation of accompanying thermal phenomena included in the analysis. The results of these attempts are reported in the studies [7-10]. In addition, the same research center conducted

theoretical analysis of the ring rolling process using a helical rolling mill equipped with three helical rolls [11]. The FEM analysis of this process (including thermal phenomena) was performed in the three-dimensional state of strain using the DEFORM-3D simulation program. Given, however, that the Simufact software is more suitable for shaping metal flow in helical rolling than DEFORM-3D, further analyses were conducted using the Simufact.forming programme. The Simufact software is an enhanced and extended version of MES.SuperForm. In the past, the MSC.SuperForm software was successfully used to model rotary piercing processes for thick-walled tubes [7-9] and cross wedge rolling processes [12-21]. Therefore, it seems justified to verify the suitability of this software for modeling processes for producing balls by helical rolling with helical tools.

The objective of this study is to investigate the effect of material parameters on the heterogeneity of metal flow in a helical rolling process for steel balls using helical rolls. Given the scope of the research, the results will be presented in the form of four closely related articles.

2. Material 100Cr6

Simufact.forming is a software product for the simulation of industrial processes provided by Simufact Engineering. It was created as a result of merging two programmes: MSC.SuperForm and MSC.SuperForge. It was developed by a group of specialists in volume forming processes. The program enables simulation of all metal forming processes, including: closed die and open die forging (cold and hot), rolling, stamping, bending, trimming, cooling, extrusion, as well as tool analysis [22].

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Bearing steel 100Cr6 is characterized by exceptionally high quality due to particularly strict production conditions. This material is required to have a narrow and strictly maintained tolerance of alloying elements and impurities. Its chemical composition is as follows: carbon 0.95 - 1.1%, manganese 0.25 - 0.45%, silicon 0.15 - 0.35% chromium 1.3 - 1.65%, phosphorus 0.025%, and sulfur - up to 0.025%.

Figure 1a shows the relationship between flow stress, effective strain and strain rate (from 0.01 to 500) for the investigated steel grade, while Figure 1b illustrates the dependence of flow stress on five temperatures (in the range between 700°C and 1250°C) for 100Cr6 steel.

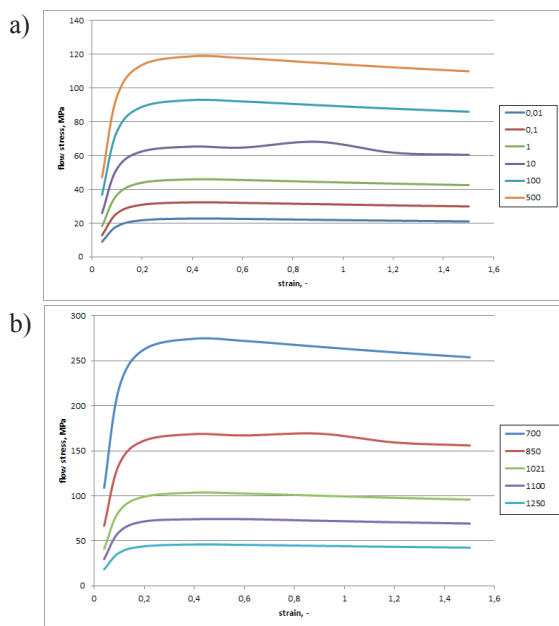


Fig. 1. Flow curves of 100Cr6 steel: a) strain rate, b) temperature

3. Numerical modeling

Prior to laboratory tests, the investigated rolling process was modeled numerically (Fig. 2.). The helical rolling process based on the conventional assumptions was modeled for four billet temperatures that were changed every 100°C, from 850°C to 1150°C, with other boundary conditions of the process being maintained unchanged. The following were measured and examined: shape progression, effective strain, medium stress, temperature, damage functions, tool wear, load and torque.

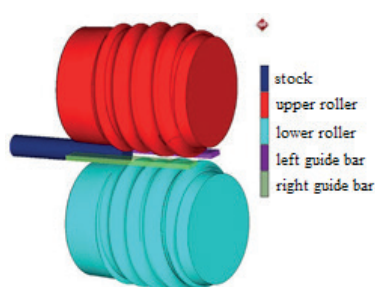


Fig. 2. Geometrical model of the rolling process for balls (isometric view), designed in Simufact.forming

Figure 3I illustrates progression of the shape of the workpiece after every revolution of the rolls. As the tool cuts into the billet, it constrains the material in the impression. The volume of the constrained material is equal to the volume of a ball being formed. In rolling, a groove with a concave surface corresponding to a round shape is also formed. In the course of forming connectors, there is a tendency for the material to come off the surface of the tools, which leads to distortion of the ball profile. In addition, at the end of the rolling process, the connector becomes excessively long, which can cause difficulty in cutting it off from the ball when the material is fully deformed. Four different simulations were performed to investigate the same process for producing balls with a diameter of 33 mm.

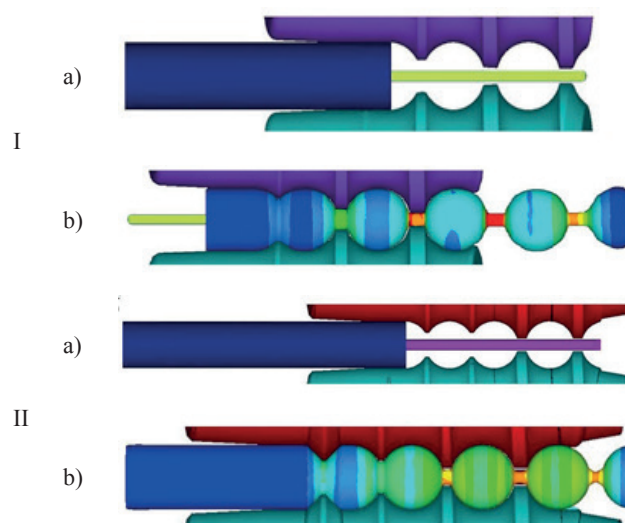


Fig. 3. Shape progression of 33 mm diameter balls in: I –helical rolling process based on conventional assumptions, II –helical rolling process with modified helical tools: a) start of rolling; b) end of rolling

The numerical simulations of the modified rolling method, i.e. helical rolling using helical tools, were also performed for four different billet temperatures: 850°C, 950°C, 1050°C and 1150°C, with other boundary conditions of the process being maintained unchanged. The numerical model of helical rolling with helical rolls is shown in Fig. 3II. It can be observed that the rolls cut into the billet periodically (after every rotation) and constrain in the impression a volume of the material that is equal to the volume of a ball to be formed. Initially, a helical wedge groove is formed (as in conventional helical rolling), and this wedge is then changed into a groove with a concave surface (corresponding to the shape of the ball). During the rolling process, the surface of the workpiece changes due to the impact of the tools. This change is most significant in the first half of the roll rotation when the wedge groove is being formed. Then, the metal flow rate becomes higher, which increases both the cross-sectional ovality of the workpiece and the width of the material-tool contact surface. During the second half of the rotation, the cross-sectional ovality is practically removed; the cross section acquires a circular shape and the material-tool contact surface is nearly linear.

Figure 3II shows the geometrical model of the helical rolling process for balls with a diameter of 33 mm designed

in the Simufact.forming program. The tools were described as perfectly rigid bodies using surface elements (triangles and quadrangles). The material was modeled with 8-nodal perpendicular elements that were concentrated in the forming zone in order to increase the accuracy of calculations. The material model (100Cr6 steel) was taken from the material database library of the simulation software. The calculations were performed based on the following assumptions: the rolls rotate at a speed of 60 rev/min; the tools are identical and have a constant temperature of 150°C; the friction factor on the tool-material contact surface is set to 1, while the heat transfer coefficient between the material and the tools is 10 kW/m²·K. In addition, the rolls are assumed to make at least 3 revolutions, which is enough for the material to leave the space between the rolls. Each revolution of the rolls was modeled in 1000 steps, which meant that the computation time was long (it took even a few days).

4. Analysis of the helical rolling process

As already mentioned, the following parameters were analyzed: shape progression of the workpiece, effective strain, mean stress, temperature, failure, tool wear, strength and torque.

4.1. Effective strain

Figure 4I shows the distribution of effective strain in the longitudinal section of the workpiece. It can be observed that the workpiece is deformed to the highest extent in the region of the connectors. The values of effective strain in this process are very high. As can be seen from the figure, at all temperature variants applied, the effective strain in the region of the connectors reaches the maximum values ranging between 21 and 25. The effective strain on the surface of the balls is between 10 and 12, and there are no significant differences between the four investigated variants of the rolling process with respect to this parameter. These high effective strain values result from the fact that the material

flows in a tangential direction, which causes unnecessary deformation of the workpiece.

Figure 4II shows the distribution of effective strain in the helical rolling process with helical rolls. It can be seen that the material is not deformed as thoroughly as in conventional rolling. It is deformed the most in the surface layers affected by the friction forces, while the layers in the input (central) axis are deformed to the smallest degree. The strains have a characteristic ring-like distribution, a phenomenon which is typical of cross rolling processes. It should also be noted that the cross-section of balls has an almost perfectly circular shape (which is an improvement compared with conventional rolling). The distribution of effective strains is similar for all variants: at the highest temperatures of the process, 1050°C and 1150°C, the effective strain reaches the maximum value of 14. These results demonstrate that the highest strains occur in the region of the connectors between the balls. At 850°C and 950°C, the maximum values of effective strain do not exceed 12. At 1050°C and 1150°C, the effective strain is higher yet does not exceed 14. The values of effective strain in the helical rolling process based on the conventional assumptions and in the helical rolling process with helical tools do not differ significantly. However, in the modified helical rolling process, the maximum values of effective strain occur almost exclusively in the region of the connectors, and they do not overlap with the surface of the balls.

4.2. Mean stress

The distribution of mean stress in the product was determined by the Finite Element Method (FEM). As can be seen from Figure 5I, the stress reaches a value of about 150 MPa at the beginning of the forming process. Towards the end of the process, these values decrease to 50 MPa. These observations apply to the four investigated variants of the rolling process.

Examining the distribution in Figure 5I, it can also be observed that the lowest stress occurs in the surface layers of the balls, which results from the compression of the material

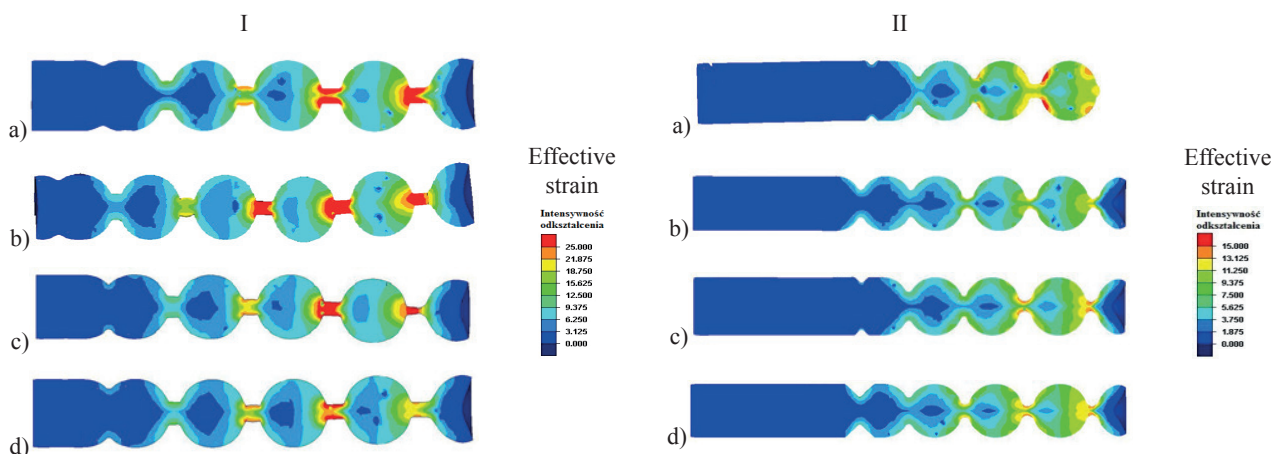


Fig. 4. Effective strain in 33 mm diameter balls produced by: I – helical rolling according to conventional assumptions, II – helical rolling with helical rolls – longitudinal section; a) 850°C, b) 950°C, c) 1050°C, and d) 1150°C

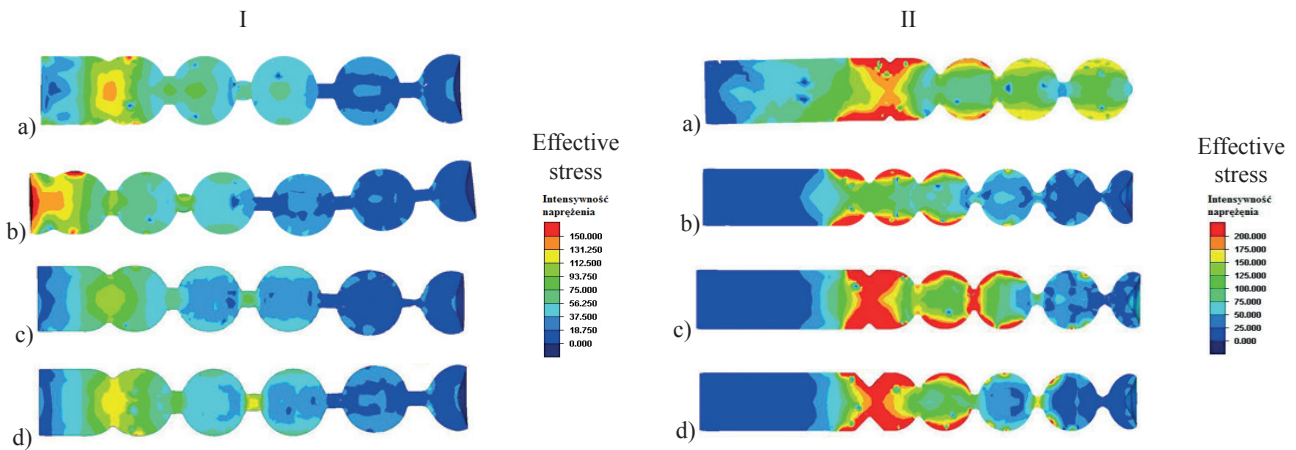


Fig. 5. The distribution of mean stress distribution in 33 mm diameter balls produced by: I – helical rolling with conventional tools, II – helical rolling with modified helical rolls – longitudinal section; a) 850°C, b) 950°C, c) 1050°C, and d) 1150°C

on the rolls. Similar values of stress can be observed in all simulated variants of the process. The stress measured in the balls produced in the investigated four temperature variants does not exceed 50 MPa.

Figure 5II shows the distribution of mean stress in the helical rolling process with helical rolls. What can be observed here is that the local maximum stress is concentrated in the material-tool contact zone. The highest stress (approximately 200 MPa) can be observed in the surface layer when the process is performed at a temperature of 850°C; the stress gradually decreases the closer it is to the axis of the tool. However, its value drops to approximately 100 MPa in the produced balls. In rotary forming processes, the regions of the highest stress shift along with rotation of the workpiece. On increasing the temperature to 1050°C and to 1150°C, the mean stress decreases to 25 MPa. Given the relatively low value of the stress, it can be assumed that rapid wear of the tools due to their excessive weight should not occur during the process. When the process is performed at a temperature of 850°C, the mean stress exceeds 75 MPa, while at three other temperature variants – it does not exceed 25 MPa. Comparing the two variants of the rolling process, lower values of mean stress values occur in the helical rolling process with helical rolls.

4.3. Temperature

The numerical simulations also involved examining thermal parameters of the investigated process. Figure 6I shows the variations in temperature in the cross section of the workpiece which occur in rolling when the billet temperature ranges from 850°C to 1150°C. The map of temperature distribution reveals that the billet maintains the preset temperature in every investigated variant of the rolling process. This observation is important given the long time that is necessary to shape the billet into a ball, i.e. approximately 4/5 seconds. Examining the results of the four simulations, it can be observed that the temperature of the balls does not fall below the temperature to which the billet was heated. The temperature of the balls after rolling is high enough to immediately subject the balls to hardening.

The next figure (Fig. 6II) shows the distribution of temperature in the helical rolling process with helical rolls. It is characteristic of this process that the preheated billet is in contact with much colder tools for a long time. This can lead to excessive cooling of the billet and, thus, have an adverse effect on the rolling process. For this reason, thermal parameters of the process were measured in the numerical simulation, too. It can be seen from Figure 6II that the temperature of the

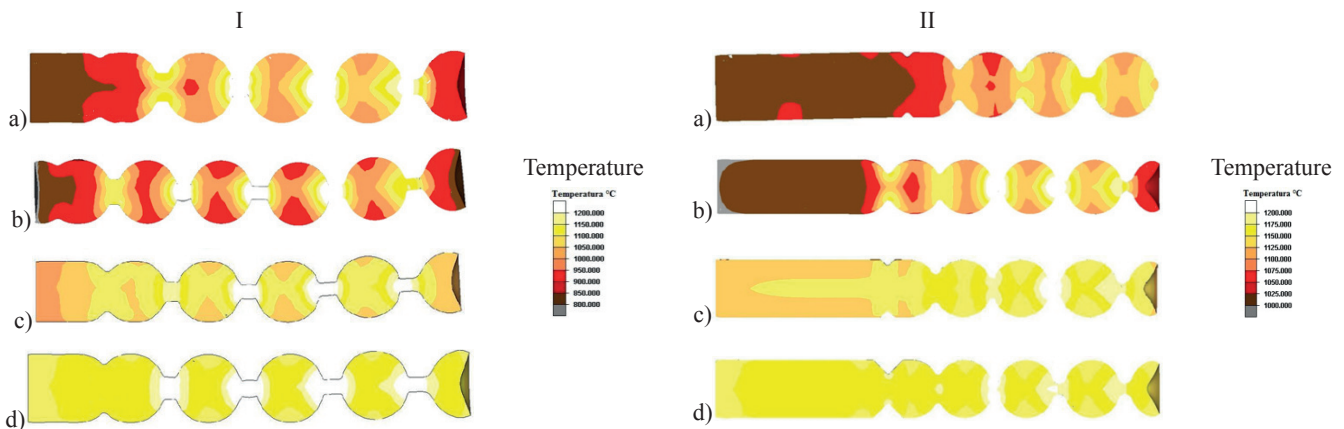


Fig. 6. Distribution of temperature in 33mm diameter balls produced by: I – helical rolling according to conventional assumptions, II – helical rolling with modified helical tools – longitudinal section; a) 850°C, b) 950°C, c) 1050°C, and d) 1150°C

balls on their edge ranges from 1000°C to 1150°C and mainly depends on the temperature to which the billet was preheated. The temperature of the balls produced in helical rolling with helical rolls is high enough to subject the balls to hardening immediately after the rolling process, as is the case with the helical rolling process run according to the conventional assumptions.

4.4. Tool wear

Metal forming causes tool wear. The most common type of tool wear in metal forming processes is abrasive wear [23]. The tool wear in rolling causes an increase in dimensional variations of the finished product. One of the most important factors affecting tool wear in metal forming processes is slipping between the metal and the tool. The slipping on the metal-tool contact surface can occur at different speeds [24 and 25], which affects the mechanism of friction.

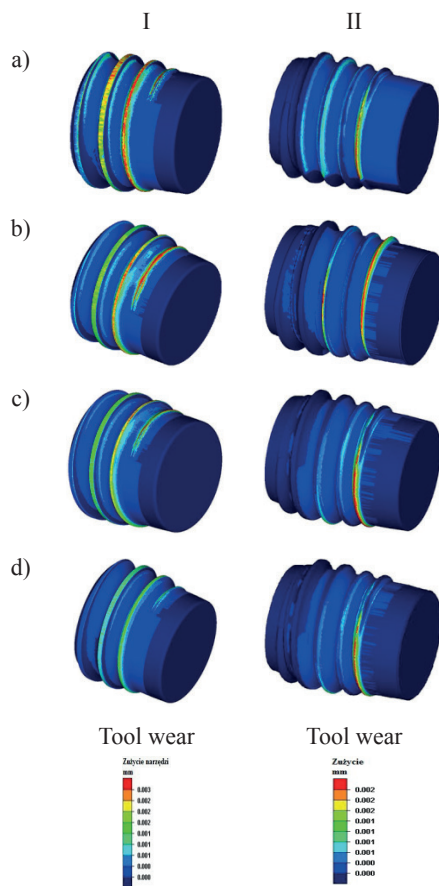


Fig. 7. Tool wear in: I – helical rolling with conventional tools, II – helical rolling with modified helical rolls; a) 850°C, b) 950°C, c) 1050°C, and d) 1150°C

Figure 7I shows the distribution of tool wear (the second roll is identical, so it is not shown in the drawing for clarity reasons). It can be noted that the tool wear decreases with increasing the temperature. The first and second coils on the roll are worn the most (out of all examined variants). The wear of the first coil is the highest because this coil cuts deeply into the material to break its coherence. By contrast, the wear of the third coil is the smallest, as it was caused in the final shaping of

the ball. When the process is run at the lowest temperature, i.e. 850°C, the wear can be seen over the entire length of the tool. At the highest temperature - 1150°C, the tool wear is smaller (it does not exceed 0.001 mm) and spread more evenly on the roll.

Figure 7II shows the distribution of tool wear which reveals that the first wedge is the most damaged as it is the first to cut into the material (as in conventional helical rolling). The figure also reveals the wear of other wedges, but the degree of their wear is much smaller and spread over a larger area of the wedge. The first wedge, just like the first coil in the conventional method, cuts in the material to the greatest extent to break its coherence and start the process of forming balls, therefore it is worn to the greatest extent. By contrast, the wear on other wedges resulting from the final shaping of the product is smaller. When the process is run at the lowest temperature, i.e. 850°C, the tool wear occurs over the entire length of the roll and – with the exception of the first wedge – its value does not exceed 0.001 mm. At the highest temperature, i.e. 1150°C, the tool wear is smaller – it does not exceed 0.001 mm (except for the first wedge), and spread more evenly on the roll.

5. Distribution of loads and torque

Loads and torques acting on the roll were determined by FEM. The determination of these parameters is essential when developing a new forming technology. The correct determination of the magnitude of loads and torques enables proper selection of both the mill and working tools. A characteristic feature of the measured distributions is their periodic character, which stems from the nature of the helical rolling process. In helical rolling based with the conventional tools, the volume of the material constrained in the impression at one complete revolution of the tool equals to the volume of a finished ball, which causes a significant increase in loads and torques. Later, in another region of the tool, the material is shaped into a ball, which leads to a decrease in loads and torques. The figures below show the above mentioned periodic character of loads (Fig. 8I) and torques (Fig. 9I) in the conventional helical rolling process for balls.

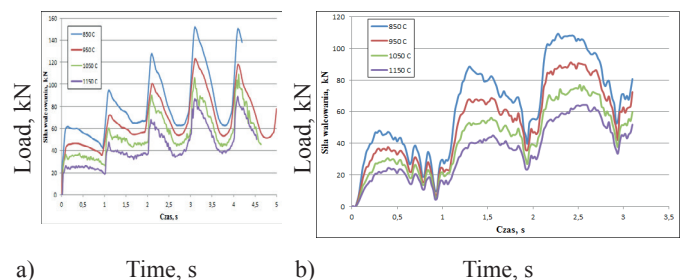


Fig. 8. Distribution of the load acting on the tools in the rolling process for balls: a) helical rolling with conventional tools, b) helical rolling with helical rolls

The diagram shows the variations in load recorded for the four temperature variants at which the simulations of the rolling process were performed. In the helical rolling process with conventional tools, the maximum values of the loads acting on the tools are relatively low: at a temperature of 850°C the loads are 150 kN, at 950°C – they are somewhat higher than 120

kN; at 1050°C – the maximum load does not exceed 110 kN, while at 1150°C – its maximum values do not exceed 90 kN. There is a clear dependence between load and temperature: the load decreases with increasing the temperature of the rolling process. When the temperature is increased to 300°C, the load decreases by approximately 60 kN. Therefore, it can be concluded the degree of tool wear will be smaller when the rolling process is run at higher temperatures.

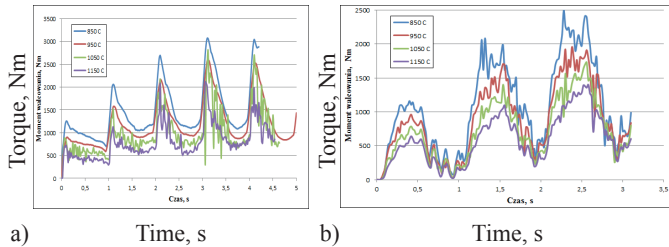


Fig. 9. Torque in the rolling process for balls: a) helical rolling with conventional tools, b) helical rolling with helical rolls

The diagram shows the variations in torque recorded for the four temperature variants at which the simulations of the rolling process were performed, i.e. at 850°C, 950°C, 1050°C and 1150°C. The maximum values of torque are relatively low: at a temperature of 850°C the torque slightly exceeds 3000 Nm, when the temperature is set to 950°C and 1050°C the torque is 2500 Nm, while at 1150°C – its maximum value is about 2.000 Nm. What should be emphasized in the helical rolling process run according to the conventional assumptions is the relationship between torque and temperature. On increasing the temperature of the rolling process, the torque decreases, and the difference in torque values between the extreme temperatures is about 1000 Nm. In the course of the simulation, the force parameters of the process, namely load and torque, were also examined. The results are illustrated in the diagrams given in Figures 8II (load) and 9II (torque). A characteristic of the measured loads and torque is their periodic character. The repeated increases in these parameters stem from the nature of the helical rolling process. The sinking of the wedge into the material first causes a rapid increase in both load and torque; then, these parameters rapidly decrease when the forming process is run on the circumference of the helical groove. Even a small overflow of the material leads to a sharp increase in load and torque, which is clearly reflected in the distribution of load at a temperature of 850°C. To further examine the distributions of load and torque in the helical rolling process with helical rolls, we will consider here the part of the curve which describes the first three seconds of the process, because after that time process disturbances can be observed. The distribution of load is shown in Figure 8II, while the distribution of torque is illustrated in Figure 9II.

The diagram shows the variations in load for four temperature variants at which the simulations were performed. The maximum loads acting on the rolls are relatively low and do not exceed 110 kN when the temperature of rolling is set to 850°C, while at 950°C – the loads are approximately 90 kN. At higher temperatures, i.e. at 1050°C, the loads do not exceed 80 kN, and at 1150°C – they slightly exceed 60 kN. Similarly to the conventional rolling process, in the modified variant of the rolling process, the load decreases with increasing the temperature. The difference in load

between the rolling processes run at a temperature ranging from 850°C to 1150°C is about 50 kN. Figure 9II shows the distribution of torque in the helical rolling process with helical rolls where disturbances to the process were recorded.

The maximum torque values are relatively low and they do not exceed 2500 Nm when the process is run at a temperature of 850°C. At a temperature of 950°C, the torque does not exceed 2000 Nm. At 1050°C – it is slightly higher than 1500 Nm, whereas at the highest temperature, i.e. 1150°C, the torque is significantly lower and does not exceed 1500 Nm. Load and torque values depend on the amount of material constrained in the helical grooves. A small overflow of the material will cause their rapid increase; however, if the grooves are filled incompletely, it will cause a significant decrease in load and torque. That is why, the strength parameters must be monitored to predict the occurrence of phenomena which could disturb the process. It can be seen from the diagram that the load in the four analyzed processes is similar, higher values occur in the rolling process run with the conventional tools. The loads range from 10 kN at a temperature of 1150°C to about 20 kN at lower temperatures, 850°C and 950°C. The results demonstrate that the variations in torque in the two investigated processes are similar. As was the case with the load, the torque is slightly higher in the helical rolling process run according to the conventional assumptions.

6. Summary and conclusions

The paper presented the results of research on producing balls by the conventional helical rolling process and by a modified rolling method, i.e. helical rolling using helical rolls. The numerical analysis of these processes was performed by the finite element method (FEM). The calculations were made using the commercial FEM-based Simufact.Forming simulation programme version 10.0. The numerical simulations were performed in the three-dimensional state of strain and took into account thermal effects occurring during the process. Moreover, the basic parameters of process kinematics were determined. In addition, the process was examined with respect to the occurrence of phenomena that could disturb process stability and, thus, have a negative impact on the quality of produced balls. Considering the investigated variants of the rolling process, it can be concluded that the best parameters of rolling are those of the helical rolling process with the modified tools.

When the billet is preheated to a temperature of 1150°C, the parameters such as load and torque as well as tool wear are the lowest. The maximum values of the loads acting on the rolls are low and they do not exceed 75 kN, while the maximum values of the torque do not exceed 1500 Nm. At a temperature of 1150°C, the tool wear is lower and has a uniform distribution on the roll that does not exceed 0.001 mm, apart from the first wedge which cuts into the material to start the rolling process, and is thus subjected to the highest wear. The temperature of the balls produced by the helical rolling process with the conventional tools is high enough (approximately 1000°C) to subject the produced balls to hardening right after rolling.

Based on the numerical and experimental results, the following conclusions can be drawn:

- balls can be manufactured by helical rolling using rolls with helical wedges;
- strains in the produced balls are distributed in layers, which is similar to cross rolling processes;
- the values of effective strain produced by the helical rolling process with the conventional tools and by the modified method do not differ to a significant extent. However, in the modified rolling method, the maximum effective strains occur almost exclusively in the region of connectors, and they do not overlap with the surface of the balls;
- lower mean stresses occur in helical rolling with the modified tools;
- tool wear is lower in helical rolling with the modified tools;
- loads and torque in the helical rolling process for balls have a characteristic periodic distribution.

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