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SKREW ROLLING OF BALLS IN MULTIPLE HELICAL IMPRESSIONS

WALCOWANIE SKOŚNE KUL W WIELOZWOJNYCH WYKROJACH ŚRUBOWYCH

This paper presents results of theoretical and experimental research on skew rolling process of balls with diameter $\varnothing 30$ mm in multiple helical tools. Numerical analysis of the process was conducted basing on finite element method (FEM), using the commercial software Simufact Forming in version 10.0. Simulations were made in the three-dimensional state of strain with consideration of complex thermal analysis, due to which progression of the products shape was determined. Distributions of strains and temperatures as well as the process force parameters were also determined. The results of numerical calculations were experimentally verified in laboratory conditions. The obtained results confirmed the possibility of semi-finished products of balls type manufacturing by means of rolling in multiple helical impressions.

Keywords: skew rolling, helical tools, balls, FEM, experiment

W artykule przedstawiono wyniki badań teoretyczno-doświadczalnych procesu walcowania skośnego kul o wymiarach $S\varnothing 30$ mm w wielozwojnych narzędziach śrubowych. Analizę numeryczną procesu przeprowadzono w oparciu o metodę elementów skończonych (MES), wykorzystując komercyjny pakiet oprogramowania Simufact Forming w wersji 10.0. Symulacje prowadzono w warunkach przestrzennego stanu odkształcenia z uwzględnieniem pełnej analizy termicznej, w efekcie czego wyznaczono progresję kształtu wyrobów. Określono również rozkłady odkształceń, temperatur oraz przebiegi parametrów siłowych procesu. Wyniki obliczeń numerycznych zostały zweryfikowane doświadczalnie w warunkach laboratoryjnych. Otrzymane rezultaty z badań potwierdziły możliwość wytwarzania półfabrykatów kul metodami walcowania w wielozwojnych wykrojach śrubowych.

1. Introduction

Mass production of balls, which are applied, e.g.: in ball mills for crushing of raw materials and as rolling elements of bearings, results in searching for new, more efficient manufacturing methods, at simultaneous improvement of technologies used so far. Conducted research works aim mainly at lowering of manufacturing costs and improving of the formed products quality. Among many methods used for balls production (machining, casting, die forging and rolling) [1-4], skew rolling processes should be taken into consideration. These processes allow for balls forming directly from a semi-finished product in form of a bar [5-8]. Skew rolling is classified as one of the most effective metal forming method of semi-finished products. This process can be continuous, without the necessity of tools stopping in order to place billet in the working space and remove the formed products. Tools lost motion does not take place, which happens in different forming methods. In consequences, these factors act on high efficiency of the process, yet, in comparison with other advantages such as small material loss, high precision of the formed products, favorable structure position and relatively easy automation, they make skew rolling processes attractive methods of balls

semi-finished products manufacturing from the industrial point of view.

Developing the technology of balls skew rolling, at Lublin University of Technology an innovatory process of balls semi-finished products forming in multiple helical impressions was worked out [9, 10]. The applied solution allows for the increase of efficiency of balls rolling several times in comparison with traditional solutions, at simultaneous improvement of the formed products quality. A complex analysis, which was conducted for the worked out process, confirmed the rightness of the assumptions. During research works, the balls rolling process was numerically simulated with application of finite element method. The obtained results were verified experimentally in laboratory conditions.

2. The essence of rolling process in multiple helical impressions

The balls forming process in multiple helical impressions is realized directly from a bar 3 between two identical rolls 1 and 2, on which surfaces multiple helical grooves are cut (Fig. 1). These grooves are separated from each other by flanges 6 and 7, which gradually increase their height and width. On the last flanges knives 8 are mounted, which sepa-

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rate the formed balls 5 from connecting them bridges. During rolling tools rotate in the same direction, putting material into backward rotary motion. The shape and stroke of helical grooves placed at rolls surfaces are chosen in such a way that in every angular position of tools constant volume of the material closed in the impression is preserved. Rolls axes are inclined obliquely (usually at the angle from $\theta = 3^\circ$ to 7° , which, in approximation, corresponds with the lead angle of the impression helical line in the sizing area) in relation to rolling axis-billet. Similarly as in the rolling process in helical one-coiled impressions, the best results are obtained when the billet diameter equals about 0.97 diameters of the finished balls. This condition results directly from the metal flow kinematics. During rolling, the reduction ratio should be imposed only on necks surfaces which connect the formed balls. In the case of application of billet of larger diameter than the diameter of the rolled ball, the reduction ratio is imposed on the formed balls spherical surfaces. This causes deformation of the rolled balls, which manifests itself by strong ovalization of the products cross section. Material coherence is very often disturbed in these cases in the central areas of the rolled balls (internal cracks appear localized in the rolled balls axis). Considering the rolling process stability, rolls diameter is assumed 5-6 times larger than balls diameter. During rolling the material is kept in the roll gap by means of the guiding devices placed between rolls. The formed balls after the rolling process roll from the machine into a water tank, where they are hardened.

During one rotation of rolls, a few balls are obtained, the number of which equals number of helical impressions. For example, in the case of application of tools with triple impressions rotating with the velocity 160 rot/min it is possible to form even 480 balls in one minute, which is practically impossible when other forming methods are used.

3. Numerical simulations of balls rolling process in three-coiled helical rolls

The rightness of the worked out forming method was initially confirmed numerically, simulating rolling processes of balls with dimensions S030 mm in triple helical impressions. Calculations were made in software Simufact Forming in 10.0 version, which was often used for the analysis of cross and skew rolling processes. The worked out for the analysis needs geometrical model of the balls rolling process in triple helical impressions is shown in Fig. 2. This model consists of two identical rolls 1 and 2, two guiding devices 3, aiming at determining the semi-finished product position during rolling and billet 4 (round bar with diameter $\varnothing 30$ mm), modeled by means of hexahedral elements. On the rolls working surfaces helical impressions are made with concave side surfaces, which radius is equal the radius of the rolled ball. Material model of steel C45 type, taken from the applied software library, was used in simulations. Moreover, it was assumed that billet material before rolling was heated in the whole volume to the temperature 1150°C and tools had constant temperature 150°C . Rolls are inclined in relation to the billet axis at angle $\theta = 6^\circ$ and rotate in the same direction with the same velocity $n_w = 60$ rot/min. On the material-tool surface of contact it was assumed that the limiting value of friction factor was $m = 1$, heat exchange coefficient between material and tools was assumed at the level of $10 \text{ kW/m}^2\text{K}$, yet, between material and the environment $0.35 \text{ kW/m}^2\text{K}$.

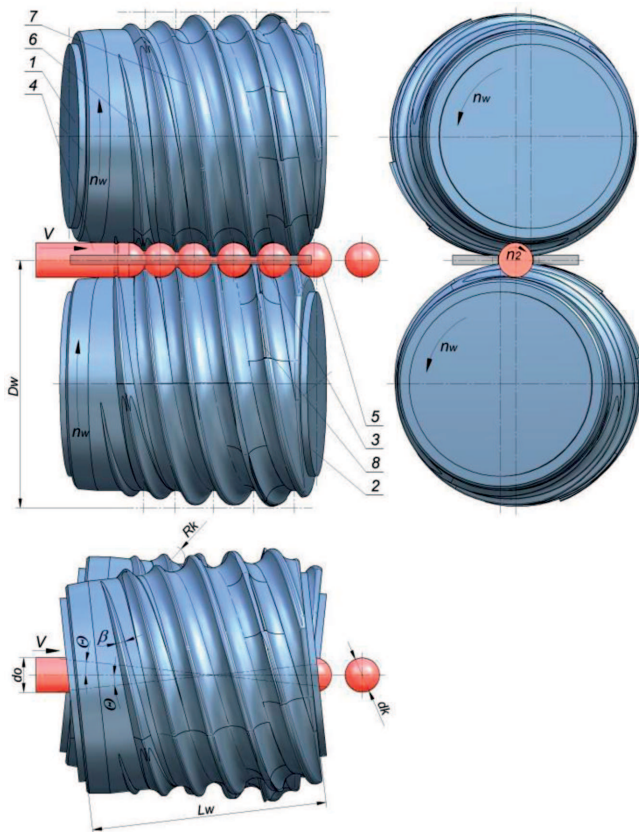


Fig. 1. Schema of the skew rolling process of balls in multiple helical impressions, (description in the text)

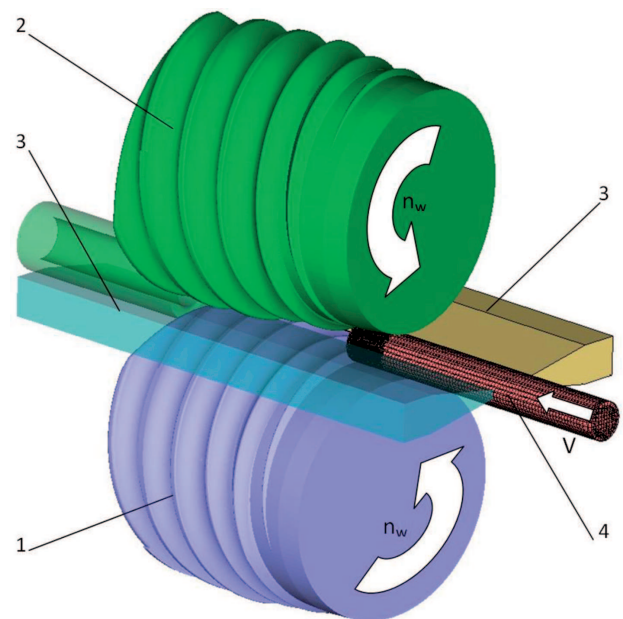


Fig. 2. Geometrical model of balls rolling process in triple helical impressions (description in the text)

4. Results of numerical simulations

In the result of conducted simulations the possibility of balls forming by means of the proposed method was confirmed. During calculations, the kinematics of metal flow at particular stages of rolling, strain intensity and temperature distributions and process force parameters were analyzed. The shape and precision of products determined numerically is at least adequate in the case of their destination for grinding medium. It can be supposed that the obtained precision will be sufficient in the case of formed elements application as semi-finished products of bearings rolling elements. Analyzing the semi-finished product shape change due to tools acting (Fig. 3), it can be well seen that moving helically rolls flanges with wedge side surfaces cut cyclically (every 120°) into billet and close in the impression material of volume equal the volume of bridge and ball.

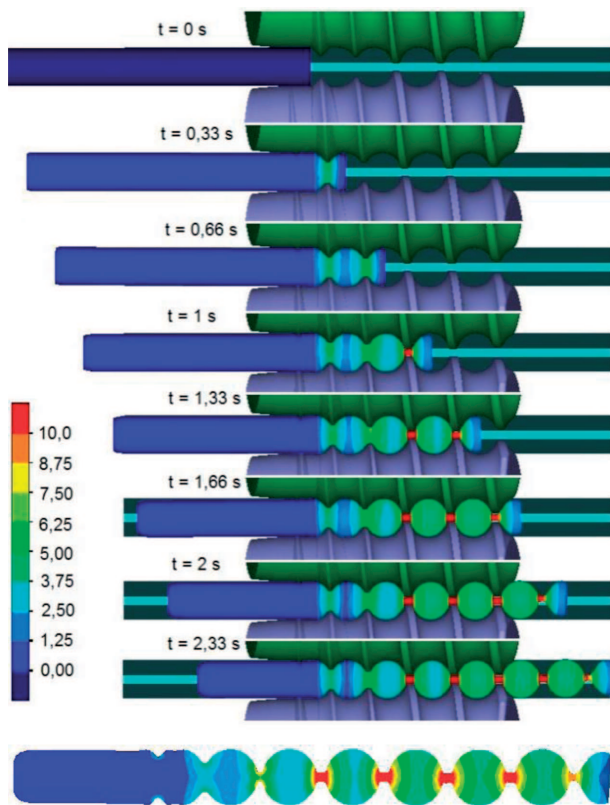


Fig. 3. The ball shape progression and effective strain distributions determined numerically in the rolling simulations in triple helical impressions

At this time, on the semi-finished product circumference is formed a ring-shaped wedge groove with conical side surfaces, which at the further stages of the process, due to flanges with concave surfaces acting, are transformed into balls bowls. Finished product is obtained after two rotations of tools. Yet, in the given rolling process, during every complete rotation of tools three balls are formed. Determined numerically balls shape is correct, free from faults and deformations. Material contacts the impression side surfaces in every point. Hence, it can be stated that the worked out solution will allow, with large probability, for proper balls forming. Due to difficulties of numerical character, in simulations the process of whole balls separating, which were connected by means of bridges,

was not realized. Figure 3 also shows effective strain distributions of the semi-finished product during rolling. Maximal deformations are localized in the connectors' areas, where the largest material plastic processing takes place. This is a characteristic feature of balls skew rolling processes, in which pressure is imposed on semi-finished product by impressions flanges.

A characteristic feature of the balls skew rolling process is relatively long time of contact of the heated semi-finished product with considerably cooler tools. It can result in excessive cooling of the formed semi-finished product, which is unfavorable for the rolling course. Hence, during numerical simulations also thermal parameters distributions were analyzed, on the basis of which temperature of the finished products was foreseen (Fig. 4). The crucial fact is that the material remains relatively large value of temperature in its volume. However, the observed decrease of temperature is relatively small (about 75°C) and it is of superficial character.

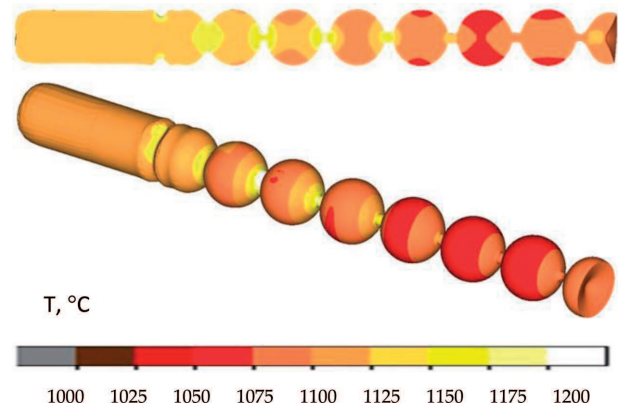


Fig. 4. Distribution of temperature determined in simulations of balls rolling process in three-coiled helical impressions after $t=2.33s$

This is the result of heat transmission from the material to much cooler tools. In the areas which undergo the largest deformation, the increase of temperature above the initial value can be observed (up to about 1200°C). Large values of temperature and even its increase (although the time of contact between the material and cooler tools is long) are the result of heat generating due to change of plastic deformation work and friction work. The formed balls temperature is so high in order to make their hardening possible after rolling.

5. Laboratory tests of balls rolling in three-coiled helical rolls

In order to verify the results of numerical simulations and to finally confirm the worked out forming method, experimental tests were made of balls skew rolling with dimensions S030 mm. A two-rolls skew rolling mill (Fig. 5), mounted at the Department of Metal Forming at AGH in Cracow, was applied in research works.



Fig. 5. Skew rolling mill built in the system of two triple helical rolls, in which rolling tests of balls S030 mm were conducted

The rolling mill is characterized by a large versatility, allowing for the application of various types of working rolls sizing. Additionally, it is possible to conduct the process in two-rolled and three-rolled system with the application of various guiding devices. The rolling mill is equipped with strain gauge measurement system registering the process force parameters (torque and pressure forces) and mechanical converters registering the process geometrical parameters such as tools rotary velocity.

In the rolling mill working space are mounted two working rolls with triple helical impressions. Additionally, in order to keep the semi-finished product in the tools working space, two guiding devices were made, mounted to the machine body. The application in tests particular rolling mill imposed on tools dimensional limits, according to which the roll working diameter was $\varnothing 215$ mm and the barrel length $L = 260$ mm. The size and shape of the worked out helical tools were presented in Fig. 6. The tools have segment construction. Working impressions of each roll consist of six tools segments 2, made from tool steel for working in hot conditions. These segments are mounted to shafts 1 of the rolling mill by means of two head nuts 3. On the segments 2 surfaces shaped grooves 7 are made, separated by flanges 5 with concave side surfaces. In the cutting area, helical wedge protrusions 4 are made, of spreading angle β and side walls inclination angle α . Knives 6 cutting necks from the formed balls are placed on the last flanges.

Steel bars of C45 type with diameter $\varnothing 30$ mm and length about 300 mm were used as billet during rolling. The semi-finished products were heated in a box-type electric furnace to the forming temperature equal 1150°C , and later they were implemented by means of tongs into a feeder positioning billet in the rolling mill working space. Billet grabbed by conical parts of rotating rolls was put into rotary motion and drawn automatically between segments, where balls forming in three-coiled helical impressions took place. During rolling the material was kept in the working space by means of guiding

devices mounted between rolls. The rolled balls after leaving the roll gap fell out at the opposite side of helical tools. During the process rolls rotated in the same direction with constant velocity $n_w = 60$ rot/min, and their axes were twisted at the angle $\theta = 6^{\circ}$ in relation to the rolling axis (billet).

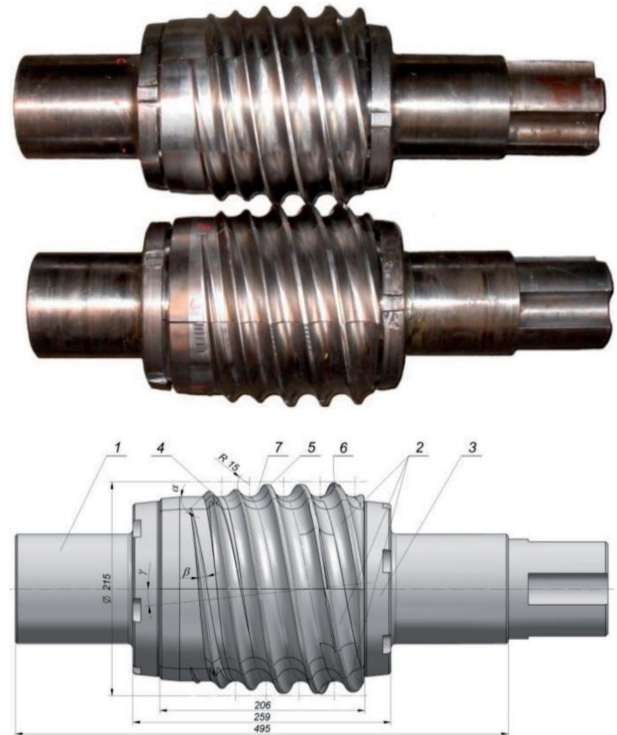


Fig. 6. Sets of screw tools segments for rolling of balls S030, mounted on the rolling mill shafts (description in the text)

In the result of conducted research works, a few sets of balls were rolled in triple helical rolls, which exemplary shape is shown in Fig. 7. The formed balls were characterized by a relatively precise circular outline, both in plane perpendicular to the rolling axis and in plane passing through the rolling axis. Internal cracks or faults in the form of the semi-finished products deformation were not observed.



Fig. 7. Balls formed in the rolling process in multiple helical impressions

Part of the rolled balls have on their circumference small infilling of the outline (about 0.2-0.3 mm) (Fig. 8) (the shape resembles circumferential crack). The cause of this phenomenon was excessive spreading of rolls from the rolling axis. In the result the material volume closed in the impression was too small for complete filling of the semi-finished product

outline. Excessive spreading of tools also resulted in incomplete separation of the formed balls, which remained connected with each other by means of necks, bilaterally cut at the formed semi-finished products surfaces. Yet, the rolled balls could easily be separated from each other. The observed infilling of the impression does not have a crucial influence on the precision of the formed balls. According to Polish Standard PN-H-94057:1998, precision of balls manufacturing by rolling, which is applied in ball mills equals ± 3 mm [11]. The obtained quality and precision are considerably higher from the required ones in the case of balls application as grinding medium.

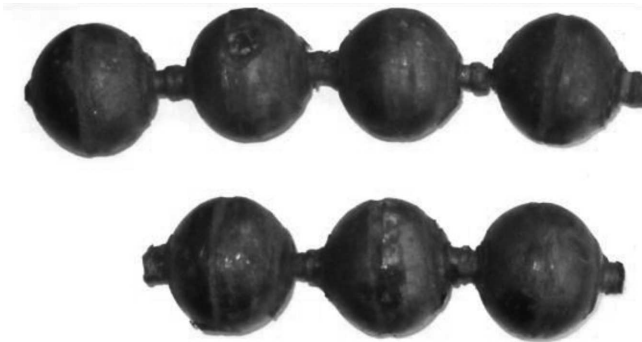


Fig. 8. Balls formed in the rolling process in multiple helical impressions connected with each other by means of necks with visible small infilling of the outline

Additionally appearing faults were limited, to a large extent, due to appropriate tools arrangement (rolls spacing). Hence the obtained precision allows for assuming that such formed products can be successfully applied as semi-finished products of bearings rolling elements.

The next Fig. 9 presents comparison of the balls shape determined numerically in simulations with the outline of products formed during experiments. A characteristic feature is large convergence of theoretical and experimental results. In both cases the shape of the obtained balls is correct, semi-finished products are connected by means of necks, which can be easily separated from the rolled balls.

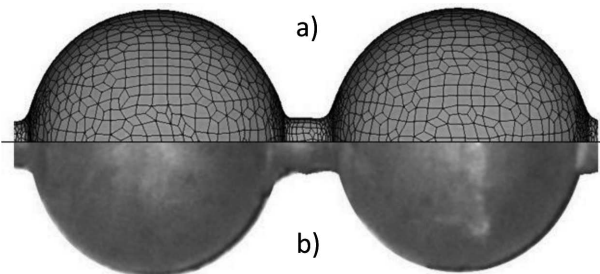


Fig. 9. The semi-finished product of ball type outline S030: a) determined numerically, b) obtained during experiments

Very often after the rolling process the formed balls undergo thermal processing (hardening), using the final temperature of the semi-finished products. Hence, it is important to determine and, next, control the process thermal parameters. During the rolling process, the distribution of temperature on the formed balls surface was registered by means of infrared camera. A characteristic feature of the obtained thermal dis-

tributions of the formed balls (Fig. 10) is large convergence with the results obtained in numerical simulations.

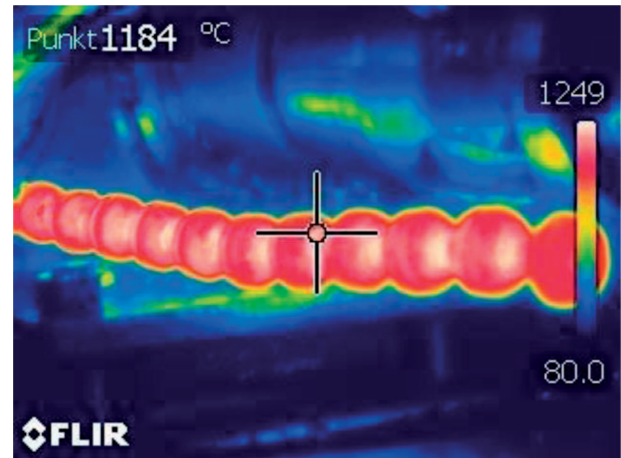


Fig. 10. Temperature measurement of the rolled balls leaving the rolling mill working space

Although the forming time is relatively long (almost 10 s), the material during rolling retained considerably high temperature, moreover, areas were observed, in which the rolled balls temperature was higher than billet initial temperature. This was caused by compensation of thermal losses (resulting from heat transmission to tools and environment) by the heat generated by plastic deformation work and friction. It should be noticed here, that temperature of the formed products (above 1100°C) is too high for their direct hardening and during the rolling process industrial realization slow cooling of the formed balls had to be used to the hardening temperature (about $850\text{-}900^{\circ}\text{C}$).

During the conducted research works the process force parameters were also monitored, and the obtained results were compared in the form of diagrams, which are shown in Figures 11 and 12. A characteristic feature of the registered forces (Fig. 11) and moments (Fig. 12) is their oscillatory course, which results directly from the process character. Every 1/3 of rolls rotation impressions wedge flanges cut into billet, separating the material volume equal the volume of ball and connecting it neck. This causes cyclic increase of forces and moments. Next, the material in the further part of the helical impression is transformed into ball, which is connected with lowering values of forces and moments.

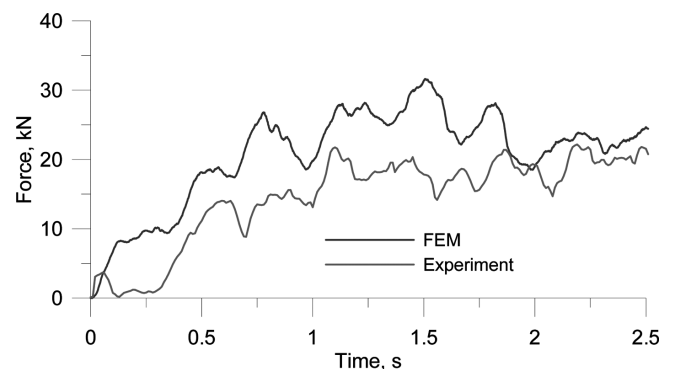


Fig. 11. Spreading force course determined during balls forming in triple helical impressions

Maximal values of forces acting on working tools, which were determined numerically (about 30 kN), are almost 20% larger than those measured during the experiment (about 25 kN). The observed differences can be caused by incomplete filling of the impression during rolling tests, which acted on lowering of forming forces. However, in the case of rolling moment, such a large difference between values determined numerically and in laboratory tests is not observed. In both cases their maximal values oscillate within the scope 1,2 kNm.

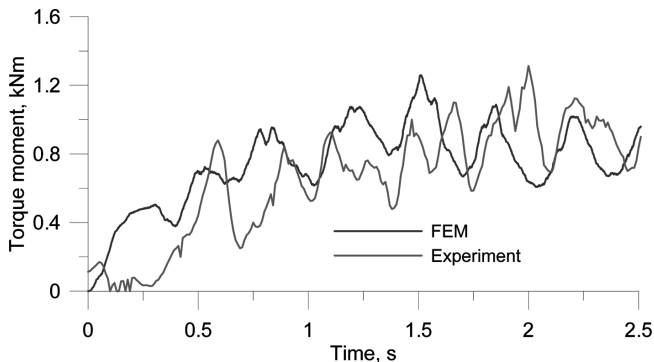


Fig. 12. Rolling moment course determined during balls forming in triple helical impressions

6. Summary

A detailed analysis, which was conducted for an innovatory process of balls rolling in multiple helical impressions, confirmed the rightness of technological and design assumptions. During the research works balls rolling process was simulated numerically with the application of finite element method. Obtained results were verified experimentally in laboratory conditions. The process course was analyzed in relation to its stability and phenomena limiting the possibility of obtaining high quality products. Force parameters were monitored, the knowledge of which is important from the technological point of view. Products obtained during research works are characterized by large precision of shape and dimensions.

Large convergence of numerical simulations results and experimental results confirms the purposefulness of application of software basing on finite element method for the analysis of rotational metal forming processes. Because of that, at the technology designing stage it is possible to optimize the process and tools shape. In consequences, implementation costs considerably lower and the precision of the formed products increases.

Summarizing, it can be stated that the worked out process allows for increasing a few times the efficiency of balls rolling in comparison with traditional solutions, with improvement of the formed products quality at the same time. These factors have a crucial meaning in the case of mass production and large – lot production, which are characteristic for products of balls type and act on lowering of manufacturing costs. Hence, the next stage of conducted research works will be a test of industrial implementation of rotational processes of balls forgings metal forming.

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