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J. TOMCZAK\*<sup>#</sup>, Z. PATER\*, T. BULZAK\***THE FLAT WEDGE ROLLING MILL FOR FORMING BALLS FROM HEADS OF SCRAP RAILWAY RAILS**

The paper describes the design of a flat-wedge reversing mill used for forming balls directly from heads of scrap railway rails. At the beginning an innovative rolling method for producing balls is presented. This two-stage method consists in forming balls from heads of scrap railway rails using plate-shaped flat tools. The first stage involves preparation of a workpiece by changing the irregular shape of the rail head into a round bar. Next, the workpiece is automatically moved to the working space of the other tool set, where forgings of balls are formed on return motion of the slide. To enable the production of balls under industrial conditions in accordance with the above concept, a flat-wedge rolling mill was designed and constructed. The results demonstrate that the machine can be used to produce balls from heads of scrap railway rails.

*Keywords:* forgings of balls, rolling, cross-wedge rolling mill

**1. Introduction**

Steel balls used as grinding media in various types of ball mills are produced on a mass scale, which makes the manufacturers seek for new production technologies enabling higher efficiency and lower manufacturing costs. Depending on the required diameter, balls can be produced by casting, die forging and rolling [1-5]. Casting processes are predominantly applied to produce balls with higher diameters (above 50 mm) as well as to produce balls made of cast iron and non-ferrous metal alloys. Die forging processes enable formation of balls with a wider range of diameters. As for higher diameters, balls are formed by hot forging, mainly on friction presses, from bars made of steel with higher carbon and manganese contents. The forging process is followed by flash trimming using eccentric or crank presses. Balls with small diameters (below 30 mm) are produced by cold machine forging [6,7]. The most efficient method for producing balls is skew rolling [8,9], as this process ensures that one ball is produced within one revolution of the rolls. This means that 160 balls with approx. 30 mm diameter or 40 balls with a diameter of approx. 120 mm can be produced per minute [10]. Forgings of balls can also be effectively produced by cross wedge rolling. Despite the fact that the origins of this technique go back to the late 19th century, the industrial application of the method was not extensively investigated until recently. This predominantly resulted from the difficulty with design of tool surface geometry. The cross wedge rolling (CWR) process for balls enables parallel formation of up to several parts (depending on the required ball diameter and the size of a rolling mill) during one working cycle

of the tools. This, in turn, leads to a higher effectiveness of the process and lower manufacturing costs. The currently applied metal forming processes for producing grinding media balls differ with respect to the type of billet they use. In most cases, the billet is in the form of rolled circular-section bars manufactured in steelworks. The cost of such billet is relatively high, often amounting up to 80%-90% of the final product's price. The manufacturing costs of producing balls can be reduced by the application of less expensive billets such as scrap and waste materials [11,12]. For example, it would be recommended to use heads cut off scrap railway rails because their current supply to the domestic and overseas markets is very high, while their price is two or three times lower than the price of commercial metallurgical products [13,14]. Given the irregular cross-sectional profile of the rail head, however, it is usually necessary that the billet be pre-formed into bars with a near-circular section. Consequently, it is indispensable to use specialist machines and employ additional operations, which leads to higher energy and labour consumption of the processes, hence decreasing the cost-effectiveness of using such materials. Given the above, research was undertaken at the Lublin University of Technology to investigate the possibility of forming balls from heads of scrap railway rails by cross wedge rolling, in one operation. The results led to the development of innovative rolling techniques for forming balls [15,16], as well as the design of a reversing mill for producing balls in compliance with the developed forming technique [17]. This paper reports a selection of the results of the research on forming balls directly from scrap railway rail heads by cross wedge rolling using a flat-wedge reversing mill.

\* LUBLIN UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING, 36 NADBYSZYCKA STR., 20-618 LUBLIN, POLAND

<sup>#</sup> Corresponding author: j.tomczak@pollub.pl

## 2. Principle of the rolling process for forming balls from heads of scrap railway rails

Previously used cross-wedge rolling methods were based on the use of billets in the form of round bars. The principle of the rolling process for forming balls directly from heads of scrap railway rail consists in forming a finished product in two stages, using two pairs of tool segments. The design of the two-stage CWR process for forming balls from scrap railway rail heads is illustrated in Fig. 1. First, the billet in the shape of rail head is put in the working space of the upper tool segment equipped with flat wedge-like flanks (Fig. 1a).

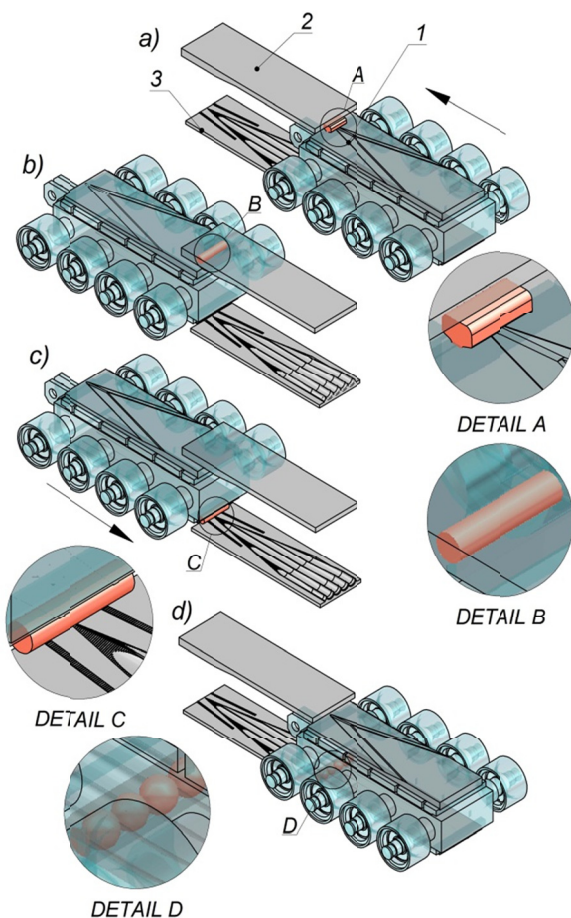


Fig. 1. Design of the two-stage rolling process for forming balls from scrap rail heads: a) start of stage one – feeding in the billet (rail head section), b) end of stage one – circular section bar produced by rolling, c) start of stage two – rolling of balls, d) end of stage two, 1– slide, 2 – upper tools, 3 – lower tools

Next, the tools are set into backward translational motion. Moving with the same velocities  $v$ , the tools cut into the billet (rail head section) and set it into rotational motion. At this movement, the rail head is formed into a circular section bar with a diameter  $d_o$  similar to a ball diameter  $D_k$ . Once the tool reaches the end position, the translational motion is stopped (Fig. 1b), and the forging is automatically moved to the working space of the lower tools (Fig. 1c), where it is positioned on two guiding paths of the tools. The working surfaces of the tools

have longitudinal protrusions separating the grooves with a semi-circular section. The next stage of the process involves starting the return motion of the tools which make the semi-finished product rotate. Balls are formed due to the action of the moving protrusions with concave lateral surfaces, and they are separated in the final stage of the process using cutters (Fig. 1d). The most important advantages of the developed technique include: the possibility of forming several balls at the same time, the elimination of lost motion of the wedges and the segment-like design of tools enabling independent regeneration of faster-wearing regions. A shortcoming of the developed technique concerns the availability of rolling mills which could be used to produce balls in compliance with the above technique. Nowadays commercial flat-wedge reversing mills are manufactured outside the European Union (mainly in China and Belarus). However, all rolling mills available on the market enable the use of only two flat tools; moreover, their return motion is lost motion. As a result, research was undertaken (under Innotech III) leading to development and design of the required flat-wedge reversing mill.

## 3. Design of the flat-wedge reversing mill

To enable verification of the developed technique for forming balls from heads of scrap railway rails, a flat-wedge reversing mill operating without lost motion was designed. principle of operation of the designed rolling mill corresponds to the schematic diagram given in Fig. 1 and the description given in Section 2. The CAD model of the developed rolling mill is shown in Fig. 2. 3D model and documentation of the flat wedge mill developed in Solid Edge software. The lower body 1 and the upper body 2 are ribbed structures made of welded steel plates. The two bodies are joined by five steel plates which form a rigid frame – 3. Both bodies are provided with the sets of wedge plates 7 and 9 as well as 8 and 10, to which the stationary tools 15 and 17 are fixed. The sets of the wedge plates enable adjusting clearance between the tools. The wedge plates 7 and 8 are moved by means of the hydraulic cylinders 18 and 20 which enable piston position measurement. The slide 11 has four axes with bearings in which rotating rolls 25 are mounted. The slide is driven by the double-performance hydraulic cylinder 21 which is mounted to the bracket 6 which is, in turn, fixed to the lower and upper bodies. The slide moves between four guides 4 (paths) fixed to the frame connecting the lower and upper bodies. The adjustment of height of the paths and the elimination of backlash are ensured by the wedge system 5 located in each path base. The slide can move thanks to the application of two guides 25 mounted to the connecting frame. The flat wedge tool 16 mounted to the upper surface of the slide and the fixed flat tool 15 are both responsible for the forming of semi-finished products (bars).

In turn, the grooved wedge tool 18 mounted to the lower surface of the slide collaborates with the lower grooved tool 17 during the forming of balls. The semi-finished product (a section of scrap railway rail) is fed into the mill by the flat-wedge tools (15 and 16) via the feeder 22 which is mounted to the upper body

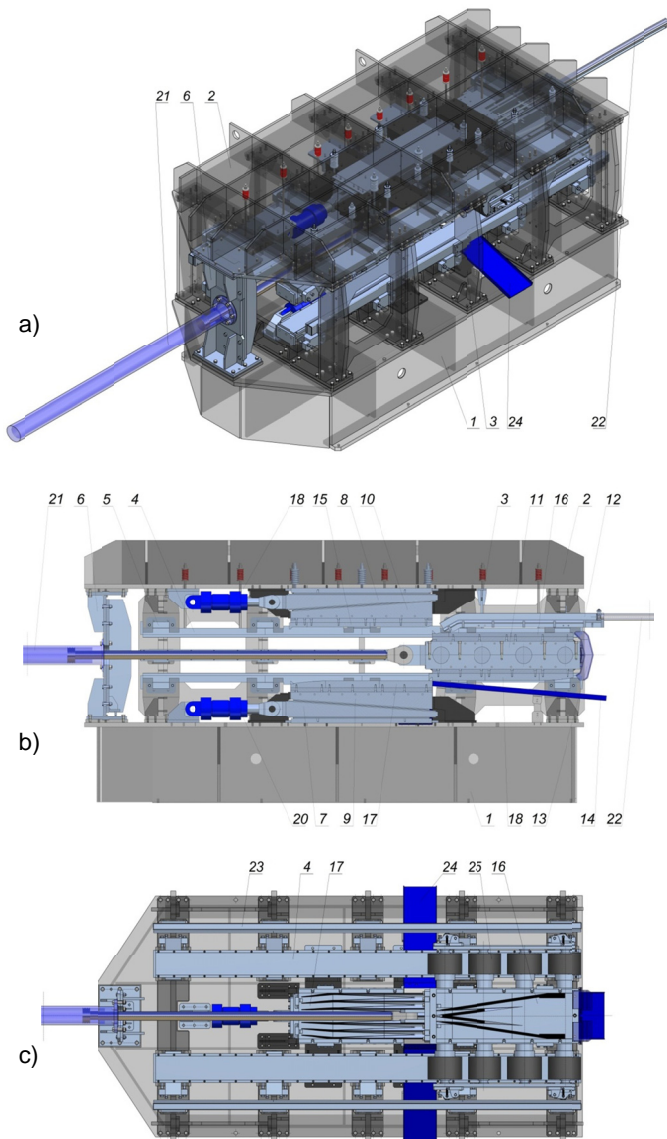


Fig. 2. 3D model of the flat wedge mill for forming balls from heads of scrap railway rails (description in the text)

of the rolling mill. The semi-finished product formed in the first stage by the upper tool set is automatically moved to the lower tool set by the guide 12 mounted to the end face of the slide. The forgings of balls leave the workspace of the mill via the sloping gutter 13, located after the output zone of the lower tool set. In addition, there are two gutters 24, one on each side of the mill, for removing end waste material cut during the forming of balls. The design of the rolling mill rests on the assumption that the slide will be under higher load during the forming of balls by the lower tool set. For this reason, it was assumed that this stage would be performed on the piston's leaving the cylinder. In contrast, the rolling of bars (preparation of a semi-finished product), which required smaller forces, would be performed on the piston's return motion. The supply to the hydraulic cylinders and liquid flow control are ensured by a hydraulic unit equipped with a three-stage pump with the capacity  $Q = 1600 \text{ dcm}^3/\text{min}$  and the maximum operating pressure  $p = 25 \text{ MPa}$ . The hydraulic pump is driven by an electric motor with the power  $N = 132 \text{ kW}$

and the rotational velocity  $n = 1450 \text{ rev/min}$ . The applied hydraulic unit enables motion of the slide with the velocity  $v = 0.3 \text{ m/s}$  in the forming of balls and  $v = 0.4 \text{ m/s}$  in the forming of bars. The most important technical parameters of the rolling mill are listed in Table 1.

TABLE 1

Technical specification of the flat wedge reversing mill for forming balls from scrap rail heads

Power of motor	kW	132
Maximal working pressure	MPa	25
Slide velocity in bar forming	m/s	0.4
Slide velocity in ball forming	m/s	0.3
Maximal force on piston displacement	kN	290
Maximal force on return motion	kN	190
Maximal tool length	mm	1300
Maximal tool width	mm	410
Minimal diameter of produced balls	mm	70
Overall dimensions L x B x H	m	9×2.4×2.4
Weight	kg	32000

#### 4. Strength analysis of the flat wedge reversing mill

Given the innovative design of the rolling mill, a strength analysis was performed by the finite element method (FEM). The analysis was conducted parallel with the design works. The numerical analysis was to examine the strength and rigidity of the machine parts under the highest load prior to construction of the machine. Next, based on the strength results, we optimized the design of the rolling mill in order to obtain the highest strength parameters combined with high rigidity. The verifying results of this final stage of design of the rolling mill (after optimization) are reported in this section. The numerical modelling was performed using the MSC Nastran solver. The numerical model was designed based on the universal pre/post graphic processor MSC Patran. MSC Nastran is a multidisciplinary application for linear and nonlinear static, dynamic and thermal analyses. Due to their complex design, the geometric models of the mill's components were designed in the CAD environment. The strength analysis was performed for two components of the designed geometrical model: the frame and the slide. To facilitate the analysis and object discretization, a number of simplifications were adopted. Welded and screw joints were removed from the model and replaced by stitched homogenous objects. In addition to this, all holes and small edges were removed from the model. The discretization process was performed in the MSC Patran environment using approximately 1 million four-node tetragonal elements in total for both objects. The numerical modelling was performed for three variants of slide position, for both the upper and lower tool set (Fig. 3). Variant 1 examined the slide position at an early stage of the rolling process (when the wedge cuts into the workpiece), Variant 2 concerned its mid-position (forming stage), whereas Variant 3 investigated the final position of the slide (sizing stage).

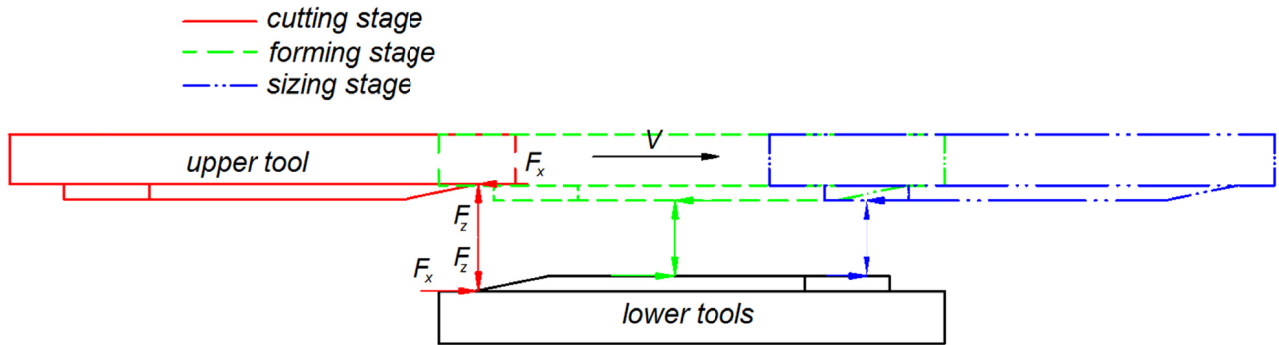


Fig. 3. Slide position in the flat wedge reversing mill during the rolling process

The loads imposed on the mill during the forming with the upper tool set are smaller than those acting on the machine in the forming process for balls performed using the lower tool set. In the rolling process for bars using the upper tool set, the mill is loaded by two forces: radial force  $F_z = 550$  kN and tangential force  $F_x = 150$  kN. In the rolling process for balls using the lower tool set, the radial force is  $F_z = 800$  kN, while the con-

centrated tangential force is  $F_x = 250$  kN. The structure's load was determined using a safety factor which was set to  $X_F = 1.2$ . This means that in everyday operation the rolling mill can be operated under a lower load. The application of the safety factor  $X_F$  resulted from unpredictable overload imposed on the rolling mill resulting from, among others, insufficient heating of the billet prior to the rolling process. The rolling mill was loaded

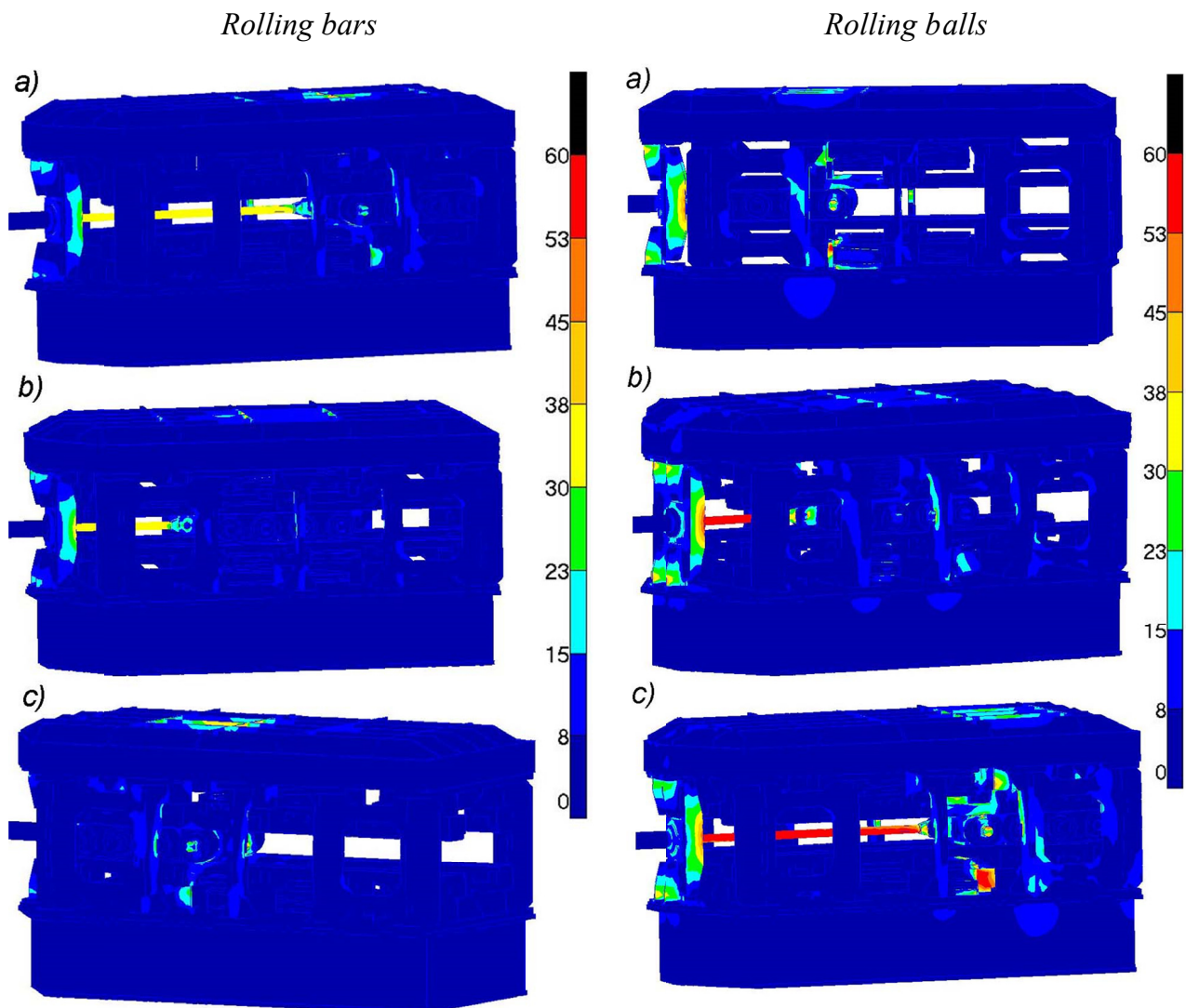


Fig. 4. Distributions of H-M-H reduced stresses (MPa) in the rolling mill in the rolling process for balls for the following rolling stages: a) cutting stage, b) forming stage, c) sizing stage

by MSC Patran's *Total Load* function which enables applying concentrated force to a defined region with a fixed surface. The area of this region was selected such that it corresponded to contact area of the workpiece and the tools. The variations in reduced stresses for the examined slide positions in the rolling processes for bars (by the upper tool set) and balls (by the lower tool set) are illustrated in Fig. 4. The maps of the H-M-H reduced stresses in the components of the rolling mill reveal that the reduces stresses do not exceed the acceptable yield point of the examined materials in any region.

During the operation of the upper tool set, the maximal stresses do not exceed 60 MPa. This value is almost four times smaller than the minimal yield point of the tested material, i.e. constructional steel S235J2,  $R_e = 235$  MPa. In the rolling process for balls, the stresses are also much lower than the yield point of the material of which the rolling mill's components are made. Here, the reduced stresses do not exceed 70 MPa, and hence they are smaller than the acceptable stresses  $k_g = 117.5$  MPa for steel S235J2. The material effort during the rolling process by the upper tool set is smaller than that during the forming

operation by the lower tool set, which results from that fact that the rolling forces during formation of a bar from a scrap railway rail head are smaller than those in the rolling process for balls.

The displacements of the rolling mill's components due to the action of load during the forming process by the upper and lower tool sets are illustrated in Fig. 5.

In the forming process for bars by the upper tool set, the slide is exposed to the highest strains ( $\Delta = 0.6$  mm); however, these strains decrease with a decrease in displacement of the hydraulic cylinder's piston rod. It must be mentioned that the rolling process performed by the upper tool set is made possible by a drawing load which is generated by the hydraulic cylinder. Consequently, the length of the piston rod's displacement will be the highest in the first stage of the rolling process. A characteristic of the CWR process is that the loads increase with duration of the process. For this reason, in the early stage of rolling, the loads acting on the mill will be much smaller than those assumed in the numerical computations. As a result, the slide's displacement will also be smaller than that obtained in the FEM analysis. The

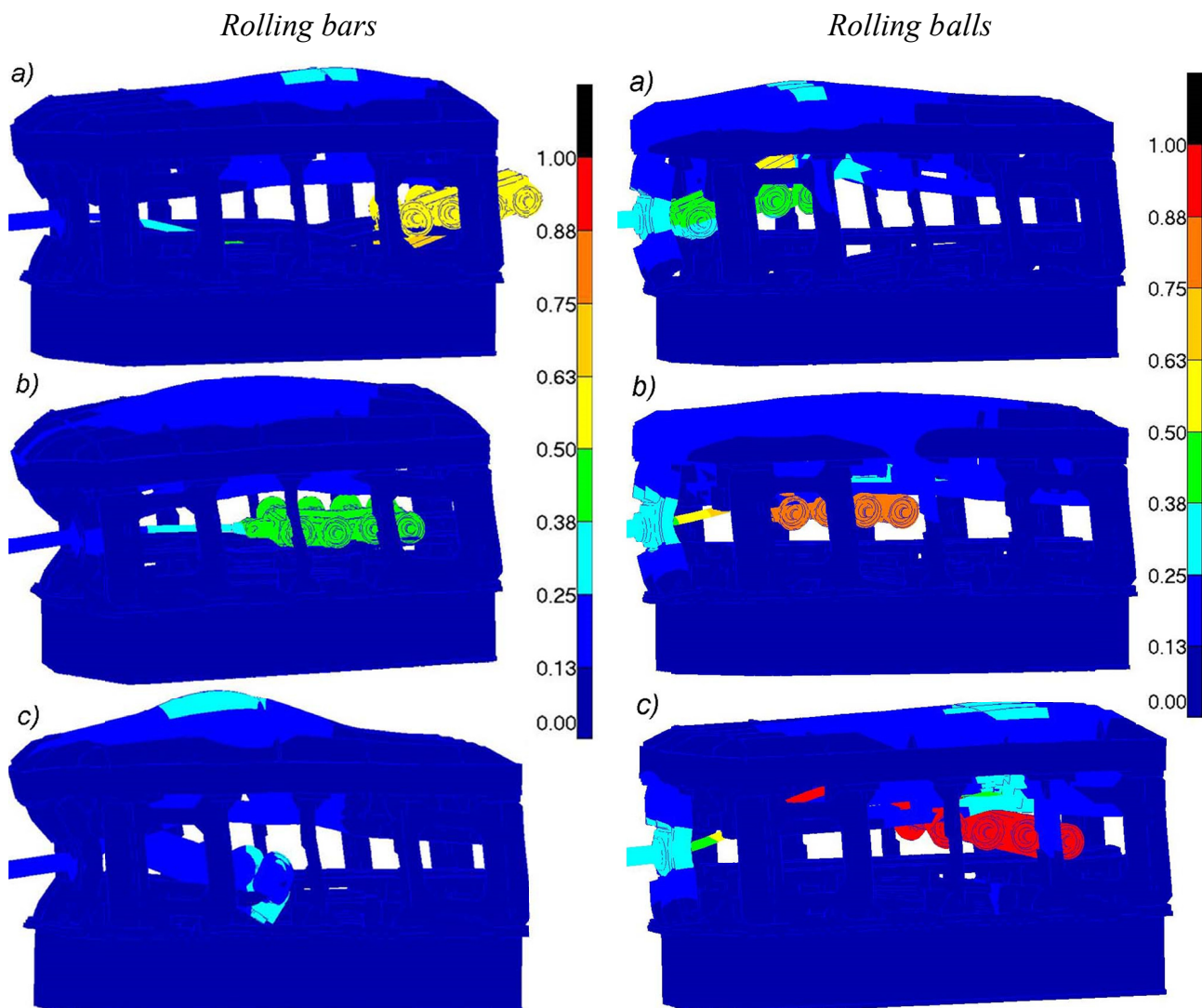


Fig. 5. Distribution of resultant displacements (mm) in the rolling mill during the rolling process for forming balls from scrap rail heads for the following stages of rolling: a) cutting stage, b) forming stage, c) sizing stage

values of displacement of other mill components due to the action of the applied load are below 0.3 mm. When the forgings are formed by the lower tool set, the displacements of individual components of the machine's body do not exceed 0.4 mm. However, the highest displacements were again observed in the hydraulic cylinder's piston rod and the mill's slide. These displacements increase with an increase in the displacement of the slide's piston rod, which results from excessive flexure of the cylinder's piston rod. In the final stage of rolling, the cylinder's piston rod can even undergo significant bending – if this is the case, the deflection can amount to approx. 1 mm. Nonetheless, the accuracy of rolling will depend on displacement of the slide towards the radial force  $F_z$ . Given that the deflections of the slide paths do not exceed 0.4 mm, one can expect that the products will exhibit certain dimensional tolerance.

### 5. Displacement tests of the flat wedge rolling mill

Based on the developed design, a prototype of the flat wedge rolling mill was constructed at the SIGMA S.A company (Fig. 6a). After mounting the tools sets in the working space of the mill, a series of tests was run to form balls with a diameter 60 mm from heads of scrap railway rails according

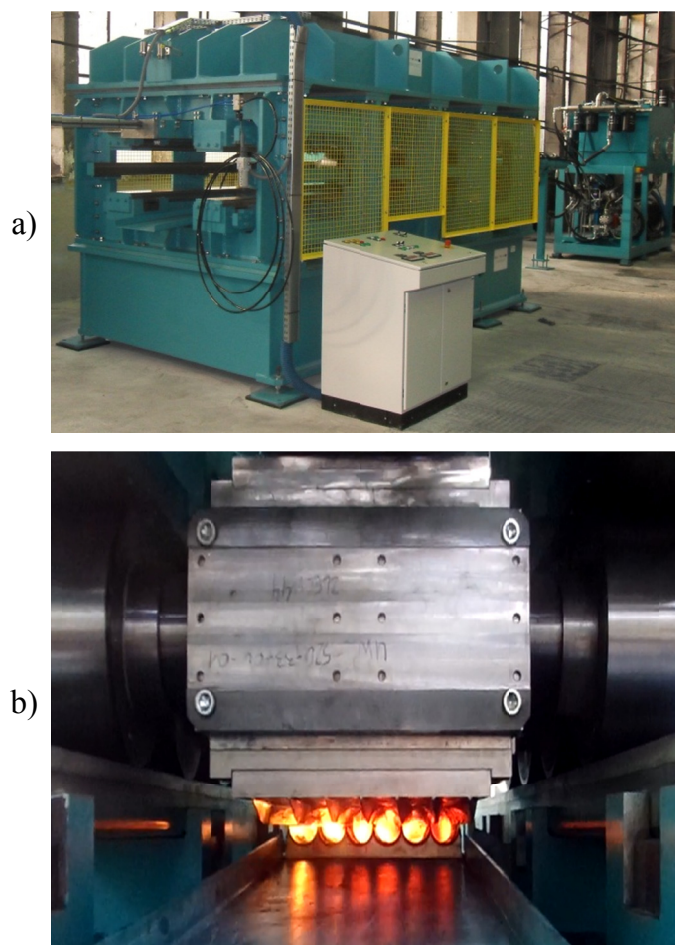


Fig. 6. Flat-tool reversing mill – a), final stage of the rolling process when balls are formed by the lower tools – b)

to the schematic design shown in Fig. 1. The billet was in the form of sections of heads of scrap railway rails described by the length  $l = 260$  mm which were pre-heated in a chamber furnace to a temperature of 1150°C. Next, the preheated semi-finished product was pre-forged by one hammer face blow in a hexagonal impression in order to remove scale and decrease the differences in cross sectional dimensions of rail heads, thereby increasing the stability of rolling in the first stage of this forming process. Thereby prepared workpiece was fed to the upper tool set where it was formed into a bar. Once the slide reached the end position, the workpiece was moved via a special guide to the feed zone of the lower tool set, where six balls were simultaneously formed on return motion of the slide (Fig. 6b). The produced balls were automatically ejected from the workspace of the mill via a sloping gutter located in its rear part.

The products and semi-finished products formed in the above mentioned stages of the process are shown in Fig. 7. Their geometry and dimensions show high agreement with the design. The quality of forgings and semi-finished products is satisfactory, too. Their surface is smooth and free from visible overlap, indentations or cracks. In the forming of bars by the upper tools set (first stage of the process), the semi-finished products have end face defects resulting from uneven deformation of the material in the section of the bar. The deformed workpiece ends were regarded as end waste and cut off during the forming of balls, so they had no effect on the quality of final products. Two end balls have slight underfill resulting from the difficulty in constraining axial flow of the metal. In contrast, the forgings formed in the central zone of the tools (four balls) exhibit complete impression fill. This defect was removed by implementing a slight modification of the tool pass.



Fig. 7. Semi-finished products and finished products produced using a flat wedge reversing mill: a) railway rail head pre-forged in a hexagonal pass, b) bar formed with the upper tools, c) forgings of balls formed with the lower tools

Fig. 8 compares the variations in forces during the rolling process for balls. It can be observed that both in the forming of bars and in the forming of balls, the maximum values of the forces are smaller than those applied in the strength analysis computations. In both cases, the early stages of the rolling process are characterized by a rapid increase in the forces, which is caused

by the fact that the tools cut into the workpiece. Examining the characteristics of the force, it can be observed that the first stage of the rolling process is characterized by much smaller values of the forces (approx. 110 kN) compared to those in the second stage of the process (approx. 220 kN). In addition to this, the irregular outline generated in the first stage of the rolling process leads to characteristic variations in the force, which results from a change in the reduction ratio during the workpiece's revolution. The variations in the rolling force are also affected by the geometry of the working tools and the value of the reduction ratio. When the rolling process is performed using the flat wedge tools (first stage of the process), the force first rapidly increases (in the cutting zone) and then becomes stable (in the forming zone) on a relatively constant level, only to decrease rapidly afterwards (sizing stage). When the rolling process is performed using the multi-wedge tools with concave flanks (second stage of the process), the force suddenly increases to reach the maximum values during the cutting stage. After that, in the forming stage, we can observe a gradual decrease in the force. This pattern results from the fact that the entire material is separated into single volumes already in the cutting stage and then formed independently into six forgings of balls in the roll passes.

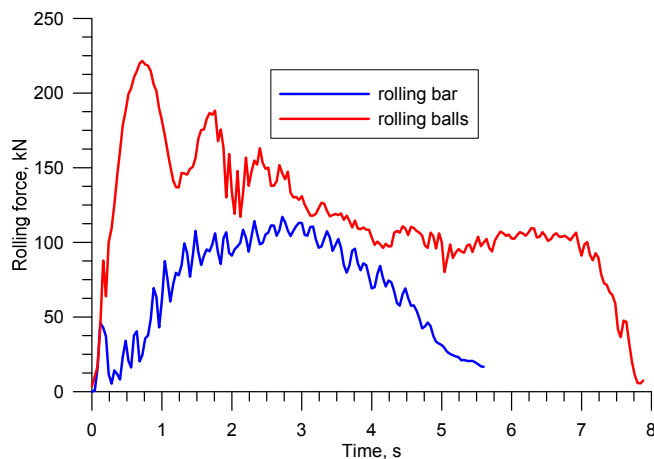


Fig. 8. Variations in the rolling force during forming balls in a flat-tool reversing mill

## 6. Summary

The results demonstrate that balls can be formed from scrap railway rails according to the proposed method using the designed flat-wedge reversing mill.

The finite element method-based multi-variant numerical analysis of the proposed reversing mill enabled verification of the machine's design. Key parts of the construction affecting its strength and rigidity were determined. The strength analysis results were used for optimization of the design, its main criteria being ensuring suitable strength, minimizing deformation of the mill components and reducing the machine's weight. The results of the displacement tests of the rolling mill, in which the variations in the forces were examined, show agreement with the design and numerical findings.

The rolling mill meets all design assumptions and enables forming the forgings of balls straight from heads of scrap railway rails, without the need of performing additional operations. As a result, due to the use of cheap material with good strength properties, the manufacturing costs are significantly lower compared to those of the techniques currently used in the industry. Another important thing is that the method enables elimination of additional technological operations connected with semi-finished product preparation and limiting to the minimum the amount of waste material generated during the forming process. This improves significantly the technique's efficiency, which is particularly vital with respect to both large-lot and mass production (which is the case with manufacturing balls for grinding media).

Although the proposed method has a number of advantages, it may pose some difficulties such as correct sizing of the tools. For this reason, it is justified that further research be conducted to determine the relationships between tool geometry, individual operational parameters and quality of produced balls as well as stability of the rolling process.

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