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STEEL BALLS FORMING BY CROSS ROLLING WITH UPSETTING

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The paper describes a process of forming four balls with a diameter of 22 mm by means of cross rolling with upsetting. The paper also presents the tool used to form semi-finished balls. Owing to the application of the finite element method (FEM), the course of the rolling process as well as temperature and strain distributions in the obtained balls could be presented. The rolling tests conducted in laboratory conditions at the Lublin University of Technology have proved that the balls produced with the developed rolling method meet the demands for grinding media used in ball mills.

Keywords: forming, steel balls, cross rolling, FEM

INTRODUCTION

Steel balls are employed on a mass scale as grinding media in ball mills which are then used for grinding metal ores, coal, used-up moulding sands, and other materials used in the economy. Owing to their spherical shape, grinding media have the most favourable (minimal) surface-to-weight ratio, which, in turn, results in decreased abrasive wear.

At present, grinding media balls are mainly produced by casting, die forging, and highly efficient skew rolling which is characterized by a good quality of obtained semi-products. In the process of skew rolling, balls are formed by means of two rolls positioned in a skew manner, which rotate in the same direction and which have helical grooves (roll passes) on their perimeter [1 - 3]. Despite its numerous advantages, this forming method is not however widely applied in industrial conditions due to the complex shape of the tools (helical rolls).

Research into a modern technology of cross-wedge rolling (CWR) has been done at the Lublin University of Technology for about twenty years [4]; and this technology may also be employed to form balls. This process is not as efficient as skew rolling, yet for its realization much simpler (less expensive) tools in the form of wedges are needed. Recently, an ever simpler method for ball forming based on the CWR technology has been developed, which is described in the present paper.

NATURE OF CROSS ROLLING WITH UPSETTING

The developed method for simultaneous forming of a semi-finished ball by means of cross rolling with flat tools is shown in Figure 1.

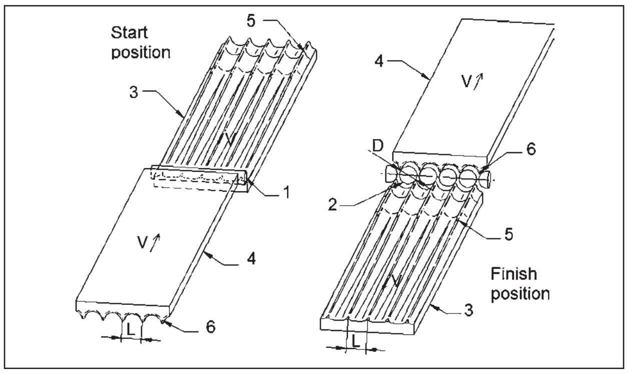

Figure 1 Scheme of cross rolling with upset ting of balls (see in the text)

According to this method, the billet (1) in the form of a bar section whose diameter is smaller than the diameter D of the ball being formed (2) is put in between two flat tools (3) and (4), which have the prongs (5) and (6) distanced from each other at the distance *L* bigger than the diameter D of the ball being formed (2). Next, the tools (3) and (4) are put into motion at the same velocity v, the prongs (5) and (6), which move in the opposite directions, cut into the billet (1) and make it rotate, reducing at the same time its diameter and cutting it into pieces with a volume equal to the volume of the ball (2). After that, the moving tools (3) and (4) and the concave surfaces of the side prongs (5) and (6) upset the cut-up semi-finished product (1), as a result of which the balls (2) whose diameter *D* is bigger than the diameter of the semi-finished product (1) are produced. The rolling process may also be conducted in a system in which only one of the tools (3) or (4) is in plane motion at the velocity v, while the other of the tools (3) or (4) does not move.

FEM NUMERICAL MODELLING

The modelling work began with designing wedge tools for the rolling process. It was assumed that balls of 22 mm in diameter would be formed by two identical flat

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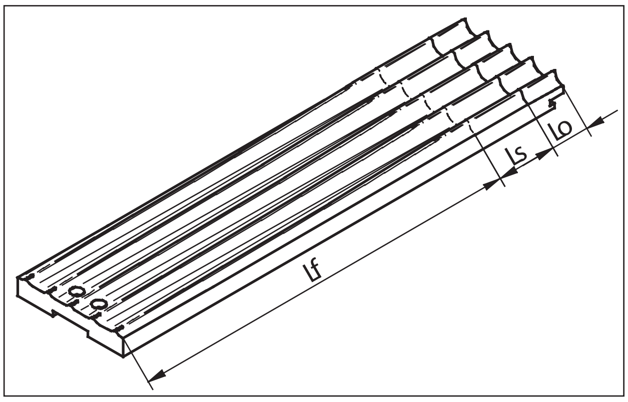

Figure 2 View of the tool used in cross rolling with upsetting of balls

tools which move in the opposite directions with the same velocity. Figure 2 shows a geometrical model of the designed tool, where three zones are distinguished: the forming zone L_f, the sizing zone L_s, and the output zone L_o. It was simultaneously assumed that the billet is in the form of a bar whose diameter dimensions are 17 mm by 120 mm. To form balls with the assumed diameter of 22 mm, it is then necessary to upset the billet by 29,4 %.

The tool model was then used to design (with process symmetry taken into account) a numerical model of rolling with upsetting for four balls of 22 mm in diameter, which is shown in Figure 2.

Made with DEFORM-3D, the numerical calculations assumed that the billet is made from rail steel grade R200 (in accordance with EN 13674-1), whose flow curves (Figure 3) are determined by plastometric tests. The choice of the material was dictated by the fact that scrapped railway rails are mostly processed into ball mill grinding media.

It was assumed that the billet material is preheated all over its volume to a temperature of 1 150 °C, the wedge tools have a constant temperature of 50 °C and they move in the opposite directions with the same velocity of 0,125 m/s, the value of friction on the material-tool contact surface is determined with the friction coefficient μ = 0,5, and the material-tool heat exchange coefficient is of 10 kW/m^{2}K.

The course of cross rolling with upsetting is presented in Figure 4. During the rolling process, all the balls are formed simultaneously by the parallel tool prongs which gradually increase their height and, at the end of the process, their width as well. A characteristic of the discussed forming method is that the material volume closed in-between the adjacent prongs is equal to the ball volume. In the initial stage of the process, the prongs cut into the material, thereby forming ring-shaped neckings.

Next, the concave walls of the prongs come closer to each other, thereby compressing the material which is between them, and, finally, they form the balls. In this process stage, individual balls should be separated; this, however, was not modelled due to the limitations regarding the applied software (it was decided that the minimal connectors between the balls should be left as they guarantee continuity of the material being formed).

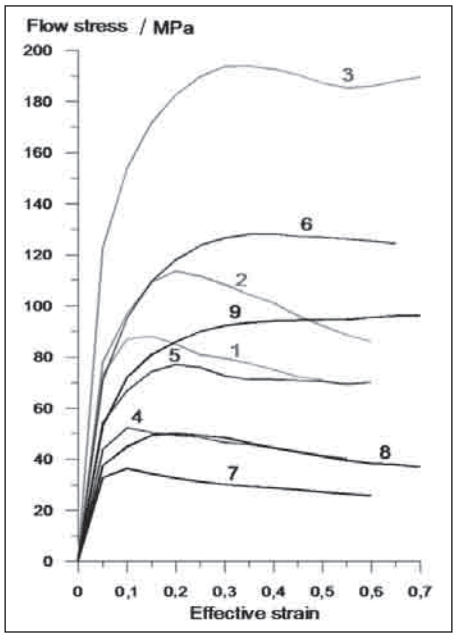

Figure 3 R200 steel flow curves at:
1) T = 1 000 °C, $\dot{\varepsilon}$ = 0,1 s^{-1}; 2) T = 1 000 °C, $\dot{\varepsilon}$ = 1 s^{-1};
3) T = 1 000 °C, $\dot{\varepsilon}$ = 10 s^{-1}; 4) T = 1 100 °C, $\dot{\varepsilon}$ = 0,1 s^{-1};
5) T = 1 100 °C, $\dot{\varepsilon}$ = 1 s^{-1}; 6) T = 1 100 °C, $\dot{\varepsilon}$ = 10 s^{-1};
7) T = 1 200 °C, $\dot{\varepsilon}$ = 0,1 s^{-1}; 8) T = 1 200 °C, $\dot{\varepsilon}$ =1 s^{-1};
9) T = 1 200 °C, $\dot{\varepsilon}$ = 10 s^{-1}

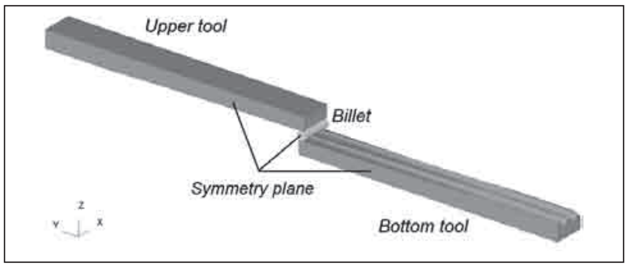

Figure 4 FEM model of rolling with upsetting of balls, with forming symmetry taken into account

Figure 5 shows the balls obtained in the process of rolling with upsetting. The ball profile is not round as it was assumed, as the ball undergoes deformation during cutting when its side surfaces get flattened due to the impact of the cutting prongs. The calculations also prove that a burr might occur in the place where the ball is separated (in the real process the burr should be smaller because the cutting knives draw closer to each other). At the same time, it should also be noted that the obtained ball shape can be considered satisfactory if the ball is to be used for grinding media where high production accuracy is not necessary (d ± 0,8).

Figure 6 also shows the distribution of effective strain. The strain has the form of ring-shaped layers, placed in parallel to the tool prongs. The biggest strains occur in the places where the balls are separated, while the smallest ones occur in the central layer where the material underwent most of upsetting.

The temperature distribution of the rolled balls is shown in Figure7.

It can be observed that the material temperature is still very high even after rolling, which makes it possi-

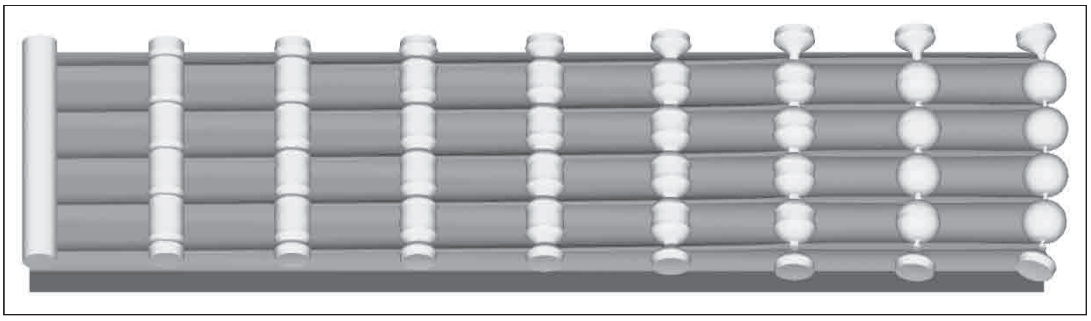

Figure 5 Process of rolling with upsetting of 4 balls with a diameter of 22 mm

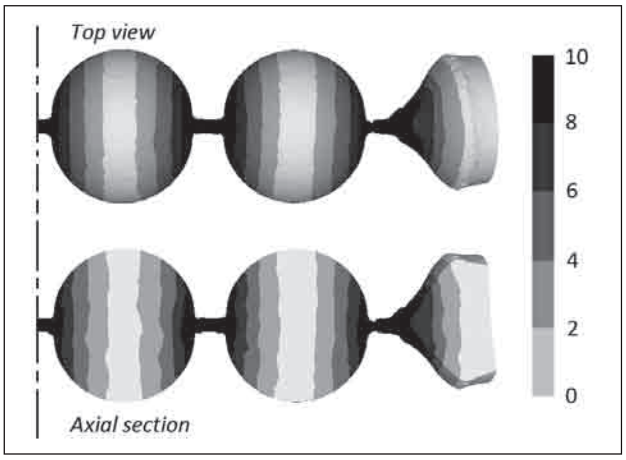

Figure 6 Effective strain distribution in the balls obtained in the process of rolling with upsetting

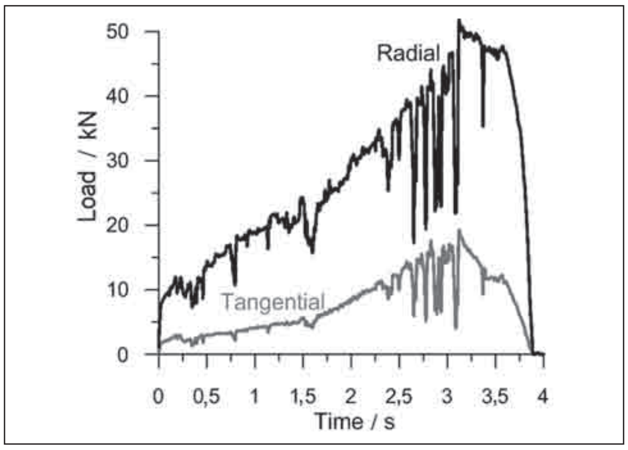

Figure 8 Numerically calculated distributions of the tangential and radial forces in cross rolling with upsetting of 4 balls with a diameter of 22 mm

ble to conduct another hardening operation (without reheating) when rolling balls for ball mill grinding media. The distributions of the radial force (which operates in the direction z – Figure 2) and of the tangential force (which makes the tool move) are illustrated in Figure 8. It can clearly be observed that in cross rolling with upsetting the forces gradually increase to reach their maximal values when the material placed in-between the prongs undergoes upsetting (at the border of the forming zone L_f and the sizing zone L_s – Figure 2). Then the forces decrease until they reach the zero value. In this connection, it should be stressed that the radial force is almost three times higher than the tangential force, which is typical of CWR processes [2].

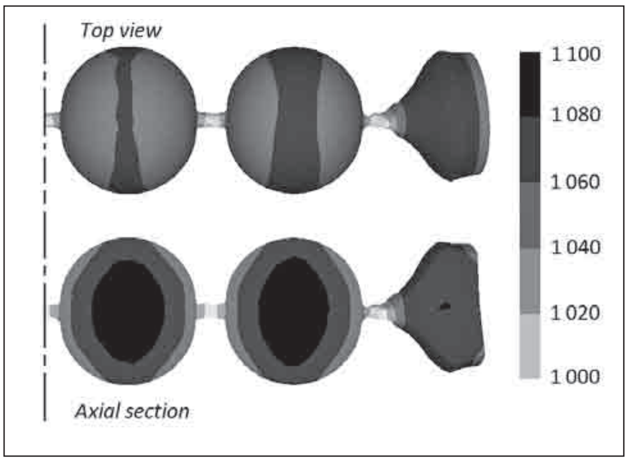

Figure 7 Temperature distribution (in °C) in the balls obtained in the process of rolling with upsetting

EXPERIMENTAL TESTS

Laboratory tests of rolling balls were carried out with the use of the rolling mill LUW-2 (Figure 9), available at Lublin University of Technology. The unit consists of a mill stand, a bottom slide, an upper slide, a power unit, and a frame. The slides move thanks to two hydraulic operators, whose maximum stroke is of 630 mm. The operators are powered by a hydraulic feeder which has an electric motor with a power of 11 kW. The maximum working pressure in the hydraulic unit reach-

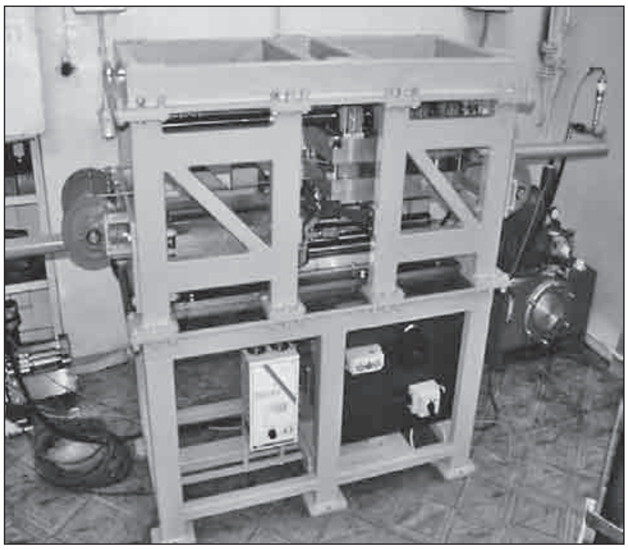

Figure 9 Wedge rolling mill LUW-2 available at the Lublin University of Technology

Figure 10 Tools for cross rolling with upsetting of balls used in the experimental tests

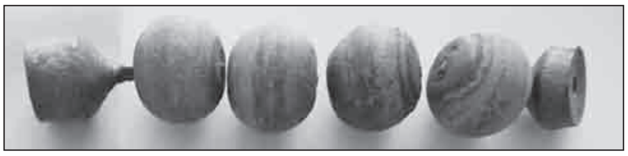

Figure 11 Balls obtained in the process of cross rolling with upsetting conducted at the Lublin University of Technology

es 20 MPa. At this pressure value, the force driving into the wedge reaches the maximum value which equals 30 kN per each of the operators.

Balls rolling with the parallel method was conducted by means of the tools shown in Figure 10. The tools are made from hot-work tool steel grade 55NiCrMoV7. A characteristic of the tools is that the prongs which form balls are parallel to the rolling direction. Additionally, the bottom tool is equipped with a special recess in which the billet made from rail steel grade R200 is placed.

The billets are heated in an electric chamber furnace until they reach a temperature of 1 150 °C. They are then placed in the recesses made in the guiding paths of the bottom tool. Once the billet position is stabilized, the rolling mill is switched on and the two tools moving in the opposite directions (with a velocity of 125 mm/s) begin to form the balls which fall on the lower plate of the rolling mill after cutting. The balls are then taken from the plate and placed on a grate to cool in free air or they are placed in a container filled with water to make them hardened.

Figure 11 shows the balls obtained in the discussed rolling process. They are of an oval shape which is similar to the one determined in the numerical calculation, yet the maximum diameter of the balls (on the central plane) is of 22,5 mm, while the minimum diameter value (in the axis of rotation) is of 20,9 mm. The dimensions are stable, as they change only within the range of ± 0,2. The produced semi-finished balls are free from internal cracks and they are characterized by a good production quality.

In the course of the rolling process, the tangential force (which presses in the bottom tool) has been analyzed and its distribution is shown in Figure 12.

The distribution is similar to the one determined by means of the FEM (Figure 8).It should yet be noted that the force determined experimentally is of a higher value, which can be attributed to the fact that the billet material becomes partially cooled when it is taken from the furnace and placed in the bottom tool recess.

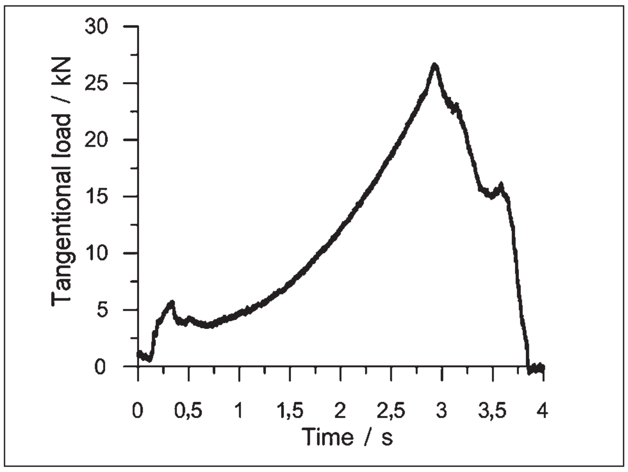

Figure 12 Tangential force distribution calculated during the tests of rolling with upsetting of four balls with a diameter of 22 mm

CONCLUSION

The conducted analytical work and experimental tests have proved that cross rolling with upsetting can successfully be employed in hot forming of steel balls. A characteristic of the semi-finished balls obtained with the suggested method is their oval shape, which does not however hamper the process of producing ball mill grinding media. In comparison with die forging, the advantages of the new production technology include: environmental friendliness (noise reduction and no need for lubricating agents), lower material consumption (no flash), and increased process efficiency (it is possible to form even several balls at the same time). Compared to helical rolling of balls, the technology of cross rolling is less expensive as it requires the use of less complex machines and tools.

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Note: The professional translator for English language is Magdalena Jung, Poland