Soft Reduction of a Cast Ingot on the Incomplete Crystallization Stage

Tatyana I. Cherkashina\textsuperscript{1,a}, Igor P. Mazur\textsuperscript{1,b} and Sergey A. Aksenov\textsuperscript{2,c}

\textsuperscript{1} Lipetsk State Technical University, Moskovskaya Street, 30, Lipetsk, Russian Federation
\textsuperscript{2} Moscow State Institute of Electronics and Mathematics, National Research University - Higher School of Economics, 109028, B. Trehsvyatitelskiy 3, Moscow, Russia
\textsuperscript{a}cherkashina_tany@mail.ru, \textsuperscript{b}mazur_ip@mail.ru, \textsuperscript{c}saksenov@hse.ru

Abstract. Numerical and physical simulation on model samples can provide data for various aspects of metal forming, without resorting to time-consuming and costly full-scale tests. This paper presents examples of modeling of the deformation of a slab with a liquid core. The use of soft reduction can enhance the homogeneity of the structure, which improves the quality of cast billets. Mathematical modeling is described here where the fluid layer is taken into account by the influence of boundary conditions in the crust in the form of ferrostatic pressure, which allows calculation of the intensity of deformation, total deformation and strain. It also provides a novel method for studying the process of soft reduction. It is based on a physical model of the slab consisting of a closed solid shell made of a calibrated lead shot and the Wood's alloy. To simulate the liquid molten metal, the interior of the shell is filled with gelatin. This approach can be applied to further studies on deformation processes and the penetration of deformation into complex metallic systems.

Mathematical Model
Basic formulas and dependencies, describing the problem of elastic-plastic deformation of the product are given in papers [1-6].

Realization of Mathematical Models in the Software Package
Mathematical models in QFORM. A numerical model was used to study the formation of the solid metal in a continuous casting process. The model is implemented in the software package QForm [6]. The object is a continuously cast slab with the dimensions of 128 \times 576 \times 1080 \text{ mm}. For research, samples were simulated in the scale 1:8, i.e., with the dimensions of 16 \times 72 \times 135 \text{ mm}. The calculation provides results for the distribution of stresses, strains, and other process parameters. There are two models developed - solid and hollow, by symmetry modeled \( \frac{1}{2} \) portion of the slab. In compression, samples were calculated with a roll radius of 75 mm and the roll speed of 0.125 m/s, as shown in Fig. 1. The material in the specimens was a medium carbon steel 1045.

![Fig. 1. The intensity distribution of strains in the program QForm](image-url)
Mathematical models in SPLEN (ROLLING 2.5). The SPLEN (Rolling 2.5) computer software was used for simulation of rolling with a soft reduction in the incomplete stage of crystallization during continuous casting. This software is developed on a basis of so called "2.5D" technique and it is able to predict the shape evolution of the rolled material as well as distributions of strain, strain rate and temperature within the volume of deformation zone [7, 8]. Experimental verifications of SPLEN (Rolling) software indicate that the mathematical models in use are accurate and consistent with experimental results [9]. The mechanical properties of deformed material were defined by the equation:

\[ \sigma = A \varepsilon^n \dot{\varepsilon}^m, \]  

where \( A = 72, n = 0.174, m = 0.134 \) corresponding to the medium carbon steel 1045 at the temperature of 1200 °C. The dimensions of a sample cross-section were 16x72 mm with the thickness of the solid cover of 4 mm. Due to the symmetry of a problem, the upper right quarter with the conditions of symmetry in the left and bottom planes was simulated. The inner liquid was simulated by the predefined pressure acting from the inside of an empty inner cavity, as shown in Fig. 2.

![Fig. 2. The initial finite element mesh and boundary condition of the simulation.](image)

The characteristics of metal forming during rolling process depend on the pressure, which affects from the inside of the solid cover. Fig. 3 presents the dependence of velocities of the specimen on the pressure obtained by the simulation of rolling with the 3 mm reduction. It assumes that the output velocities of liquid inner and solid cover are identical and equals to \( v_1 \). The input (\( v_{S0} \)) and output (\( v_t \)) velocities of solid were calculated in the program SPLEN (Rolling 2.5) during the simulations. Then, by the changing of the size of the inner cavity and assuming the incompressibility, the input velocity of inner liquid (\( v_{L0} \)) was calculated for each applied value of pressure.

It can be seen from Fig. 3 that the input velocity of the inner liquid is lower than the input velocity of the solid cover if the pressure is below 32 MPa. For the typical value of the steel density (8000 kg/m³) the pressure is 0.08 MPa on one meter height. Hence, the values of pressure in the product slab are below 1 MPa, and from the dependences presented in Fig. 3, we can expect that some part of liquid metal will be pushed back from the deformation zone. In the given geometry and pressure of 1 MPa, the reduction of the inner zone is 30% greater than the reduction of the solid part.
Comparison of the results. The results obtained in the program and QForm SPLEN (Rolling 2.5) have similar features, but different numerical values. This is due to the fact that the program does not allow to set internal pressure in QForm and the liquid phase is not simulated, leading to different strains from those in SPLEN (Rolling 2.5).

Physical Modeling of Rolling with Soft Reduction

Physical model of a slab with a liquid core. To maintain physical modeling, the metal object consists of two phases, and the conditions are equal to those in the real deformation process of the formation of plates based on the recommendations given in [4]. In a modelling example, the initial size of the sample were $H_0 = 16$ mm, $B_0 = 72$ mm, $L_0 = 135$ mm, with the wall thickness of 4 mm. A method of drawing of the coordinate grid has been proved to work well in processing of metals under pressure for studying of deformation in inside layers of continuous volumes [10]. However, the modeling a sample of a slab with a liquid core is not obviously possible because of the small thickness of a wall and the necessity of creation of the internal pressure simulating the ferrostatic pressure of the liquid melt on the hardened crust of an ingot. Therefore, the modeling sample have executed in the form of the closed solid-state cover of a squared shape. The cover represents a composite from spherical grains of the base metal. The space between the grains is filled by a metallic filler. Considering that in the model it is necessary to provide uniformity of properties, lead was used as the base and the filler was the Wood's alloy. Such choice of the components was reasonable because the Wood's alloy contains a considerable share of lead, which is used traditionally for modeling hot by rolling rinks [11]. Besides, the fusion temperature of lead is considerably higher than that of the Wood's alloy that guarantees an invariance of initial geometry of grains at the model manufacturing. They also possess sufficient diffusive gripping that will provide uniformity of deformation in the vicinity of crystallized part of the composite. In addition, differences will allow defining the borders of components while investigating the change of the sizes of the grains in the course of deformation. As the spherical grains, cast hunting shot № 9 (GOST 7837-76) were used. The presence of liquid metal in a cover was imitated through a nipple located on a face side by pumping gelatin (GOST 11293-89) under the pressure of 0.1 MPa. The hypothesis about the possibility of assessing the stress-state affected in deformation is to reconfigure spherical grains. The idea of the method is that the change of the original spherical shape to the elliptical one in deformation will reveal the main directions of strain. In this case, the diameter of the sphere, because of the equality of grain volumes before and after the deformation, is determined by direct measurement of the main diagonals of the ellipsoid through the equation:

$$d = \sqrt[3]{\ell_1 \ell_2 \ell_3},$$

(2)
Experimental procedure. Deformation of the model samples was carried out on a laboratory rolling mill 250 at OMD of Lipetsk State Technical University. The total reduction in 2 passes of the both samples was adjusted to 3 mm (2 mm in the first pass and for the second pass 1 mm).

After deformation, samples were cut across the direction of the rolling rinks. Primary visual inspection of the sections showed that the basic deformation of grains has occurred along the narrow sides while along the wide one they remained non-deformed. A typical section is presented on Fig. 3 where the cross-sections of grains on a narrow side look like an ellipse but on the wide they are circles.

Because the lead fraction located along wide and narrow sides had changed differently in the course of deformation from the initial form for the further research fragments to which the fraction form represented the greatest interest for studying of the deformed condition of samples after cobbing have been chosen. Before extraction position of grains of an investigated fragment photographed with use of a coordinate grid, the modeling sample locally heated up, and at the liberated grain measured the main diagonals ellipsoid – \( \ell_1, \ell_2, \ell_3 \) (fig. 4). In a vicinity of the selected grain the values of the main strains are:

\[
\varepsilon_1 = \frac{\ell_1 - d}{d}, \quad \varepsilon_2 = \frac{\ell_2 - d}{d}, \quad \varepsilon_3 = \frac{\ell_3 - d}{d},
\]

where \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) – the main relative deformations; \( d \) – initial diameter of fraction (2). Further, on known dependences it is possible to define other characteristics of the deformation condition.

The greatest interest is the deformation along a narrow side of a sample, where the results of the measurements indicated strains to be greatest. Along the wide sides deformation is insignificant.

As observed from Fig. 4 the lead fraction placed at the lateral faces of the slab is being squeezed in Y direction. This fact is consistent with simulation results, presented in Fig. 5 which represents the distribution of y-deformation tensor component \( \varepsilon_y \). The values of \( \varepsilon_y \) are negative that corresponds to compression at the vertical direction and they are grater absolutely on the lateral sides of the slab.

![Fig. 4. The sample after deformation; a - the specimen cross-section; b - the form of the fraction taken from the sample](image_url)
Conclusions

The results obtained by physical and numerical simulation of the effect of rolling with a soft reduction in a stage of incomplete crystallization shows that the solid cover of a slab deforms mainly in lateral faces. The zone of intensive plastic deformation does not penetrate into the center of top and bottom faces of slab. This was confirmed by the fact that the form of lead fraction situated along the wide faces of the specimen is almost spherical whereas at the lateral faces of a slab it has an elliptical shape after the rolling. This observation agrees with the results of numerical simulation.

The numerical simulation allows estimation of the influence of pressure of the liquid inner part on the characteristics of forming. The analysis of the features shows that the relative amount of inner liquid is reduced during the rolling process due to displacement of some part of the liquid, pushed back from the deformation zone by the rolled solid cover. In the given geometry, the reduction of inner zone is 30% greater than the reduction of the solid part.

References
