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*Bezusov A.T., Choporov O.N., Danylina H.V., Guido M., Kukhar V.V. et al.*

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INNOVATIVE TECHNIK UND TECHNOLOGIE, INFORMATIK  
*INTELLECTUAL CAPITAL IS THE FOUNDATION OF  
INNOVATIVE DEVELOPMENT*  
INNOVATIVE ENGINEERING AND TECHNOLOGY, INFORMATICS

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## KAPITEL 3 / CHAPTER 3. RESEARCH AND IMPROVEMENT OF ROLLING PARAMETERS AT THE STECKEL MILL

ИССЛЕДОВАНИЕ И УЛУЧШЕНИЕ ПАРАМЕТРОВ ПРОКАТКИ НА СТАНЕ СТЕКЕЛЬ  
ДОСЛІДЖЕННЯ І ПОЛІПШЕННЯ ПАРАМЕТРІВ ПРОКАТКИ НА СТАНІ СТЕКЕЛА

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### Introduction

Modern technologies including the thermomechanical controlled rolling process (TMCP) and the latest equipment [1, 2], which have been developed recently, have given impetus to the production of rolled products with a new level of quality characteristics, including requirements for microstructure, shear fracture area, increased impact requirements, correlation of yield strength or tensile strength and others. When developing a new technology and mastering a new product mix, with increased requirements, manufacturers and scientists are faced with problems [3, 4] that require further study. The way of solving one of these problems, namely providing increased requirements for these quality parameters, is to study the influence of the deformation degree on the stress distribution that occurs in the metal during rolling, and its penetration through the thickness of rolled products along the deformation zone at different temperatures.

Among the research methods that are conducted to study the rolling process, currently the most common are analytical methods [5-10] and methods of simulation [11-19], which have become widespread with the development of computer technology. The application of mathematical modeling methods in processes of metals processing by pressure allows to satisfy several purposes at the same time: to minimize expenses for research and development of technological processes in the conditions of actual production, to carry out in-depth research of processes of plastic deformation occurring in the experimental deformation zone; to compare the results of the study through the simulation with the actual results that have been obtained during production in order to identify bottlenecks in the technology. Among others, through simulation, in-depth study of temperature processes [20-23] has become widespread which are integral parts of the modern metal-forming process.

Due to the modern development of different variants of technological processes, such as normalized rolling, thermomechanical rolling, with all its varieties, the principles of which are the interaction, under certain conditions, between temperature and deformation, there are still questions about their integrated study and impact on the final products quality [24-26].

The objective of the work is to investigate the stress and strain distribution under the conditions of the rolling process at the Steckel mill by the finite-elements method



(FEM); compare the calculation results of the rolling force parameters obtained by the simulation based on the Abaqus CAE 6.14-2 software with the actual results obtained at the Steckel mill.

In recent years, the number of Steckel mills, which have undergone several evolution stages, has increased considerably. Modern mills are able to produce not only heavy deformed electrical and carbon steels but also high-strength and corrosion-resistant microalloyed steels. The dimensional range has also extended significantly: modern mills can produce rolled products with a thickness of 1.5...50mm, including plates, instead of the thicknesses of 2...12mm. The weight of slabs used is up to 70tons. State-of-the-art Steckel mills are equipped with all the necessary equipment to produce high-quality rolled products.

In keeping with the advancing digital technologies, rolling technology mathematic simulation methods are now widespread. Various authors offer mathematical models with different structures, which are developed by various methods [27-34]. It should be pointed out that most of the papers are based on the finite element and finite differences method.

Various error levels, which can be obtained by using these models, determine their further application from the simulation at the education program level [31] to the target technology design.

In paper [32], the authors suggest using the developed model to design the controlled rolling or thermo-mechanical [33] rolling technologies, since it takes into account thermo-physical and structural parameters [34]. However, the authors do not indicate the error level that this model allows to obtain. The model proposed by the authors [35], which involves the influence of metal anisotropy in the rolling process, is particularly interesting. However, other authors do not indicate or take into account this feature.

The error indicated by the authors in paper [36] is determined by rolling force and is 1.42MN on average. It should be noted that the abovementioned error depends on the rolling force level, which is shown in the graphs in paper [36]. The simulation error indicated by the authors in paper [37] is  $\pm 10\%$ , and in paper [38] the error is up to 15.6% in the first pass and then decreases. In paper [39], the error is less than 8%. Thus, different error level of the authors makes it possible to differentiate the proposed models for the calculation of more or less sensitive production methods. However, the use of models with the least error in the design of controlled or thermo-mechanical rolling technology, as shown in papers [32, 33], is unanimous.

It should be mentioned that most mathematical models, which have been developed by engineering companies and tested on the existing equipment, have



limited access.

Thus, the use of models for the development of rolling technology, its optimization greatly facilitates this process, reduces technological errors and mitigates risk of obtaining products of unsatisfactory quality, to which, among other things, the authors [29, 34, 40, 41] paid attention.

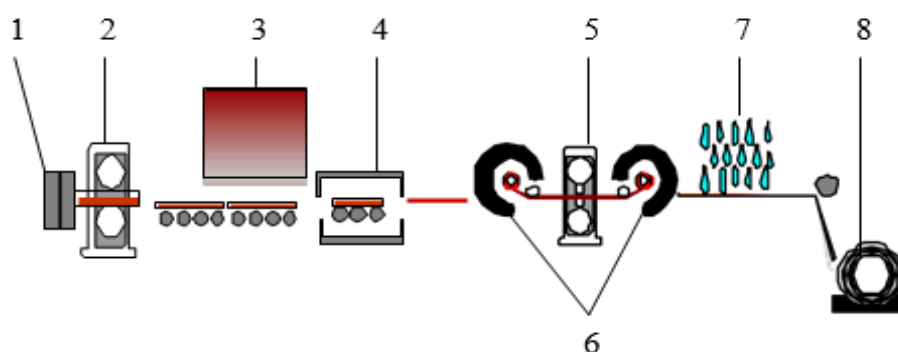
The relevance of development and mathematical model evaluation for the conditions of the Steckel mill at Ferriera Valsider SpA is driven by the need to master new technologies in order to expand the product mix and meet the needs of the European market.

The paper is focused on evaluating mathematical model of hot-rolled coil rolling at the Steckel mill at Ferriera Valsider SpA (metallurgical plant which has been successfully operating in Verona (Italy); it belongs to METINVEST Group since 2001), for the further development of technology.

### 3.1. Materials and Methodology

#### 3.1.1. Input data and methodology for finite element simulation

The technological process and power characteristics of the Steckel mill at Ferriera Valsider plant, Italy have been investigated in the work. The scheme of the main technological line for the production of hot-rolled coils at Ferriera Valsider plant is shown in Fig. 1. The characteristics of the experimental product mix and the actual rolling schedule are given in Table 1-3.



**Fig. 1. Scheme of the technological line for the production of hot-rolled coils at Ferriera Valsider plant:** 1 – stand with vertical rolls; 2 – roughing stand of 3170; 3 – pushing continuous heating furnace; 4 – through roller furnace; 5 – Steckel stand 1780; 6 – furnace coilers; 7 – equipment of laminar cooling; 8 – coiler

**Table 1**

**The product mix of slabs and coils under study**

| Heat number | Slab number | Steel grade | Slab cross-section, [mm] | Coil cross-section, [mm] |
|-------------|-------------|-------------|--------------------------|--------------------------|
| 81518       | A1/02005400 | S355JR+AR   | 220×1520×9800            | 15×1500                  |

**Table 2**

**The chemical composition of the steel grade S355JR+AR under study**

| Heat number | Mass fraction, [%] |       |      |       |       |      |      |      |       |       |       |      |       |       |       |
|-------------|--------------------|-------|------|-------|-------|------|------|------|-------|-------|-------|------|-------|-------|-------|
|             | C                  | Si    | Mn   | P     | S     | Cr   | Ni   | Cu   | Al    | Ti    | Nb    | Mo   | V     | N     | As    |
| 81518       | 0.14               | 0.023 | 1.40 | 0.014 | 0.003 | 0.05 | 0.18 | 0.02 | 0.035 | 0.005 | 0.034 | 0.01 | 0.005 | 0.007 | 0.005 |

**Table 3**

**The actual rolling schedule of heat number 81518 on the stands of the Steckel mill**

| Rolling mill                          | Pass | H, [mm] <sup>1</sup> | h, [mm] <sup>2</sup> | Reduction, [%] | Diameter of working rolls, [mm] | Rolling speed, [m/s] | Temperature before pass, [°C] | Rolling force, [MN×100] |
|---------------------------------------|------|----------------------|----------------------|----------------|---------------------------------|----------------------|-------------------------------|-------------------------|
| Two-high rolling mill 3170            | 1    | 221.3                | 200.49               | 9.40           | 1050                            | 2.20                 | 1090                          | 1007                    |
|                                       | 2    | 200.49               | 178.82               | 10.81          | 1050                            | 2.20                 | 1068                          | 904                     |
|                                       | 3    | 178.82               | 158.36               | 11.44          | 1050                            | 2.20                 | 1068                          | 1000                    |
|                                       | 4    | 158.36               | 139.55               | 11.88          | 1050                            | 2.20                 | 1044                          | 1017                    |
|                                       | 5    | 139.55               | 120.54               | 13.62          | 1050                            | 2.20                 | 1073                          | 1015                    |
|                                       | 6    | 120.54               | 103.88               | 13.82          | 1050                            | 2.20                 | 1023                          | 1077                    |
|                                       | 7    | 103.88               | 87.23                | 16.03          | 1050                            | 2.20                 | 1055                          | 1121                    |
|                                       | 8    | 87.23                | 71.81                | 17.68          | 1050                            | 2.20                 | 1009                          | 1243                    |
|                                       | 9    | 71.81                | 57.87                | 19.41          | 1050                            | 2.20                 | 1027                          | 1254                    |
|                                       | 10   | 57.87                | 46.82                | 19.09          | 1050                            | 2.20                 | 1027                          | 1246                    |
|                                       | 11   | 46.82                | 37.16                | 20.63          | 1050                            | 2.20                 | 1041                          | 1397                    |
| Fore-high rolling mill 1780 (Steckel) | 1    | 37.16                | 23.95                | 35.55          | 620                             | 4.06                 | 999                           | 1957                    |
|                                       | 2    | 23.95                | 18.98                | 20.75          | 620                             | 4.06                 | 958                           | 1351                    |
|                                       | 3    | 18.98                | 15.17                | 20.07          | 620                             | 4.06                 | 920                           | 1195                    |

<sup>1,2</sup> thickness before (H) and after (h) the pass, mm



It should be noted that in order to exclude calculation errors associated with the fixation of the actual rolling temperature on the passes at the rolling mill, in the Abaqus CAE system simulation, the results of the analytically performed calculation have been used [6]. To build a model of metal physical and mechanical properties processed in the system CAE (Complete Abaqus Environment) it is necessary to specify its density, elasticity and plastic properties. The finite-element (FE) model of a hot rolling process is built for the rolling process of steel grade S355JR+AR according to the requirements of EN 10025-2, with the chemical composition given in Table 2. The following parameters were set in the Abaqus CAE system: density  $7.8E09 - t/mm^3$ ; Poisson's ratio – 0.3. The Young's modulus has been given depending on the metal temperature  $t, ^\circ C$  according to the following dependence [42]:

$$E = (213.286 - 4.877 \times 10^{-2}t - 3.33 \times 10^{-5}t^2 - 2.778 \times 10^{-8}t^3) \times 10^3, \text{MPa.} \quad (1)$$

The deformation resistance (flow stress) of the metal was determined according to the method of L.V. Andreyuk and G.G. Tyulenev, by the chemical composition [43]:

$$\sigma_s = S_{\sigma_{0D}} u^a (10\varepsilon)^b (t/1000)^c, \quad (2)$$

where  $u$  – is the strain rate,  $s^{-1}$ ;  $\varepsilon$  – engineering strain;  $t$  – is the deformation temperature,  $^\circ C$ ;  $S_{\sigma_{0D}}$ ,  $a$ ,  $b$ ,  $c$  – coefficients for each steel grade, which are determined by the corresponding dependences, taking into account the content of chemical elements in steel [43].

The transformation of the deformation resistance values  $\sigma_{s_{true}}$ , obtained by the method of L.V. Andreyuk and G.G Tyulenev, and the engineering strain values  $\varepsilon_{in}^{pl}$  for implementation in the Abaqus CAE environment has been performed according to the following method:

$$\sigma_{s_{true}} = \sigma_s (1 + \varepsilon); \quad (3)$$

$$\varepsilon_{true} = \ln(1 + \varepsilon); \quad (4)$$

$$\varepsilon_{in}^{pl} = \varepsilon_{true} - \frac{\sigma_{s_{true}}}{E}. \quad (5)$$

The deformation resistance  $\sigma_{s_{true}}$  in the Abaqus CAE environment has been given depending on: the engineering strain ( $\varepsilon$ ) in the range of 0.0-0.8; strain rate ( $u$ ) in the range of 0.0-40.0  $s^{-1}$ ; deformation temperature ( $t$ ) in the range of 800-1200  $^\circ C$ . In the calculations according to equation (2), to obtain zero values for the engineering strain and the strain rate in the Abaqus CAE system, the values respectively equal to 0.001 and 0.01 have been used. The values of deformation resistance  $\sigma_{s_{true}}$  and the



engineering strain  $\varepsilon_{in}^{pl}$  have been processed by formulas (3) and (5).

To reduce the calculation time in the model, according to the software developer's recommendations, process symmetry has been used. Processing of the FE analysis results consisted in the analysis of stress and strain fields. Reactions at the roll reference point have been used to analyze the power parameters of the rolling process. Graphs obtained in the Abaqus CAE environment have been exported to MS Excel in numerical form.

### 3.1.2. Materials of Research

The main equipment of the Steckel mill train at Ferriera Valsider SpA consists of 6-zone pusher-type reheating furnace for heating of the slabs, which is fed by natural gas, mill 3170 for the rolling of heavy plates and semi-finished rolled stock for the Steckel mill, which involves two-high stand with a rolling force of 25MN, and edger mill, 7-zone pusher-type roller hearth furnace for intermediate heating of the semi-finished rolled stock, which is fed by natural gas. The Steckel mill includes four-high stand 1780 with a rolling force of up to 24MN and batch-type furnace with drum-type coils, which is fed by natural gas. There is also laminar cooling unit for 41m strip after rolling, which allows cooling metal at a rate of up to 40°C/s. The coilers are designed to coil a strip with a thickness of up to 20mm. Layout of the main equipment at the Steckel mill at Ferriera Valsider SpA is shown in Fig. 1.

In the mathematical model, used for calculations, the input parameters are as follows: dimensions and chemical composition of the workpiece, burnout loss in the reheating furnace, power, speed, and geometric characteristics of the main equipment used for the coil production.

The model, which takes into account equipment features and factors that affect rolling temperature at the Steckel mill, has been used as a basis when developing rolling process model [27].

To check the mathematical model, the following actual data on rolling of the coils, the product mix of which is shown in Table 4 have been used.

**Table 4**

#### Product mix of slabs and coils used to check the mathematical model

| Heat code | Slab No.    | Steel grade | Slab section, [mm] | Coil section, [mm] |
|-----------|-------------|-------------|--------------------|--------------------|
| 81518     | A1/02005400 | S355JR+AR   | 220 x 1520 x 9800  | 15 x 1500          |
| 83270     | A1/02008812 | S355J2+N    |                    | 12 x 1500          |
| 83749     | A1/02008905 | S355J2+N    |                    | 10 x 1500          |



The chemical composition of the slabs used to check the mathematical model is used in Table 5.

In the simulation, actual steel resistance to the plastic deformation has been calculated using actual chemical composition of the slabs in accordance with Andriiuk and Tiulenev methods.

**Table 5**

**Chemical composition of steel, which is used to produce rolled products to check the mathematical model**

| Heat code | Mass fraction, [%] |       |      |       |       |      |      |      |       |       |       |      |       |       |       |
|-----------|--------------------|-------|------|-------|-------|------|------|------|-------|-------|-------|------|-------|-------|-------|
|           | C                  | Si    | Mn   | P     | S     | Cr   | Ni   | Cu   | Al    | Ti    | Nb    | Mo   | V     | N     | As    |
| 81518     | 0.14               | 0.023 | 1.40 | 0.014 | 0.003 | 0.05 | 0.18 | 0.02 | 0.035 | 0.005 | 0.034 | 0.01 | 0.005 | 0.007 | 0.005 |
| 83270     | 0.14               | 0.015 | 1.34 | 0.017 | 0.004 | 0.04 | 0.02 | 0.02 | 0.033 | 0.005 | 0.034 | 0.01 | 0.005 | 0.005 | 0.005 |
| 83749     | 0.13               | 0.009 | 1.37 | 0.014 | 0.004 | 0.05 | 0.03 | 0.03 | 0.037 | 0.005 | 0.030 | 0.01 | 0.005 | 0.006 | 0.005 |

The gap between the working rolls is to be converted to the thickness of the rolled products, including the stand stiffness, for the use of actual data on the rolling conditions [44, 45].

The stand stiffness of two-high stand (mill 3170) has been calculated on the basis of roll gap data, actual length of the rolled product and rolling force in this pass:

$$S_r = \frac{F}{H_f - H_G}, \tag{6}$$

where  $F$  is the rolling force, MN x 100;  $H_f$  is the actual thickness of the rolled product calculated on the basis of measurements of the actual width and length of the rolled product in the last pass and the weight of the rolled product, mm;  $H_G$  is the roll gap in the last pass, mm.

Thus, the calculated stand stiffness (mill 3170) is 180MN x 100/mm. The data used for calculation are given in Table 6.

**Table 6**

**Data for calculation of two-high stand stiffness, mill 3170**

| Parameter            | Unit measure | Value | Parameter             | Unit measure  | Value |
|----------------------|--------------|-------|-----------------------|---------------|-------|
| $F$                  | [MH x 100]   | 1397  | Rolled product length | [mm]          | 56280 |
| $H_G$                | [mm]         | 29.4  | Workpiece weight      | [t]           | 24.48 |
| Rolled product width | [mm]         | 1494  | $S_r$                 | [MH x 100/mm] | 180   |



The following formula has been developed to calculate the four-high stand stiffness (Steckel mill 1780 condition), depending on the rolling force, based on the improved equation:

$$S_f = 191.16 \ln(F) - 1032.7. \quad (7)$$

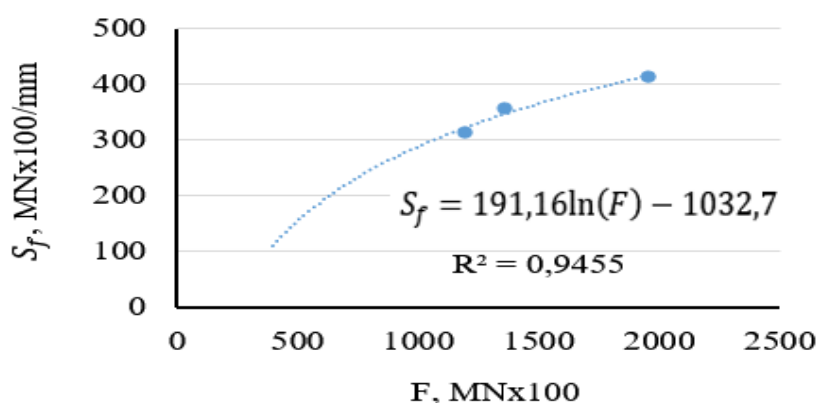
Formula (7) is obtained on the actual data, the processing results of which are shown in Fig. 2.

To calculate the deviations in the thickness of the rolled product due to change in stiffness, depending on the rolling force in the stand (mill 1780), it is possible to use the dependence obtained on the basis of actual data, and equation (7):

$$\Delta H = 2.0242 \ln(F) - 10.646. \quad (8)$$

The comparison of deviations in thickness, when changing the stiffness of two-high stand (mill 3170) and four-high stand (mill 1780), calculated on the basis of dependencies (6-8) is shown in Fig. 3.

When increasing the rolling force from 500MN x 100 to 2400MN x 100, deviation in thickness due to change in the stand stiffness (mill 3170) increases from 3mm to almost 14mm, and from 2 mm to 5mm for the mill 1780. The comparative results show a significantly higher stand stiffness (mill 1780) and, consequently, higher quality of the finished rolled product, as well as the need to take into account deviations in the thickness of the workpiece coming from the mill 3170 when implementing the rolling conditions in the stand of the mill 1780.

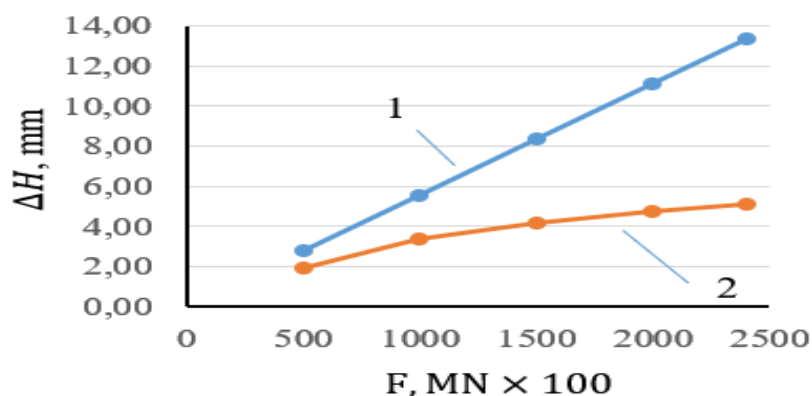


**Fig. 2. Dependence of two-high stand (Steckel mill 1780) stiffness on the rolling force**

Taking into account the stiffness of both stands, there have been made calculations of the rolling parameters for coils, the product mix of which is given in Table 4. The actual resistance to deformation has been calculated in accordance with the method of L.V. Andriuk based on the chemical composition of steel. Using these parameters, high-speed rates and torques of the main electric motors of the mills of 3170 and 1780 (Steckel) have been calculated. The calculation error has been



calculated with the use of various parameters such as temperature and rolling force.



**Fig. 3. Comparison of thickness deviations due to change in stiffness of two-high stand, mill 3170 (1), and four-high stand, 1780 (2), depending on the rolling force**

## 3.2. Finite-Element Simulation of Rolling

### 3.2.1. Results of Research

The calculation of steel grade S355JR+AR rolling processes from slabs with dimensions of 220 mm × 1520 mm × 9800 mm and the final coil dimensions of 15 mm × 1500 mm in the Abaqus CAE environment has been carried out by passes for the roughing stand, rolling mill 3170 and for rolling mill 1780 with furnace coilers (Steckel), taking into account the features of technology and equipment. The results of calculations of equivalent stress fields (S) and equivalent plastic strain (PEEQ) through the demonstration passes in the rolling mill stand 3170 are shown in Fig. 4. It should be noted that in the figures, the fields of equivalent stress (S) have the dimension “MPa”.

Based on the dynamics of changes in the shape of the fields, intensity or level of equivalent stress S in layers, we can make the conclusion as for the penetration of the deformation through the thickness of rolled products. As known, the final properties of the rolled products begin to form at the stage of roughing rolling. Therefore, obtaining data on the occurrence of such a phase in the metal allows to improve processes of the design, development and improvement of the technology in relation to characteristics of a particular condition and the material being processed.

When modeling the rolling schedule of steel grade S355JR+AR in mill stand 3170, the beginning of the deformation penetration into the entire depth of the semi-rolled product, in thickness, is observed in the sixth pass. Here a solid layer or stress



field begins to form which equals 90 % of the maximum equivalent stress in this pass, under other appropriate rolling conditions. The equivalent plastic strain at the exit of the deformation zone, in layers, depending on the depth of penetration into the thickness of the rolled products, varies from 0.121 up to 0.208, the difference is 0.087.

Upon further rolling, in the subsequent passes, there is an increase in the length of this continuous stress field together with an increase in the value of the equivalent plastic strain. In pass 8 the formation of a layer of maximum stress is being observed with its subsequent expansion and mixing with the stress layer, which equals 90 %, taking into account the size of the deformation zone. The equivalent plastic strain at the exit of the deformation zone in layers depending on the depth of penetration into the thickness of the rolled products varies from 0.184 up to 0.246, the difference is 0.062.

Based on the results obtained, one can conclude that the technological efficiency of the rolling process, which is being simulated, starts to occur from the sixth pass. The deformation, which is carried out before the sixth pass, is mostly aimed only at achieving the required shape of the rolled products or semi-rolled product. The technological efficiency means the implementation of the rolling process with a significant impact on internal processes occurring throughout the thickness, and not only on the surface layers of the rolling products. The results of the calculation of the equivalent stress fields  $S$  and equivalent plastic strain PEEQ along the passes in the rolling mill stand 1780 (Steckel) are shown in Fig. 5.

When modeling the rolling schedule of steel grade S355JR+AR in mill stand 1780 (Steckel), in all three passes there is the penetration of deformation into the entire depth of the semi-rolled product thickness under other appropriate rolling conditions. In this case, the equivalent plastic strain at the exit of the deformation zone in layers is almost the same throughout the depth / thickness of the rolled products and has the following corresponding values: 0.422, 0.228, and 0.208-0.238.

Based on the obtained results it is possible to conclude that when rolling in mill stand 1780 (Steckel), through all passes, the penetration of deformation is carried out through the entire thickness of rolling products. The maximum equivalent stress and the stress equaled 90 % of the maximum have a continuous layer throughout the entire thickness of the rolled products, taking into account the size of the deformation zone.

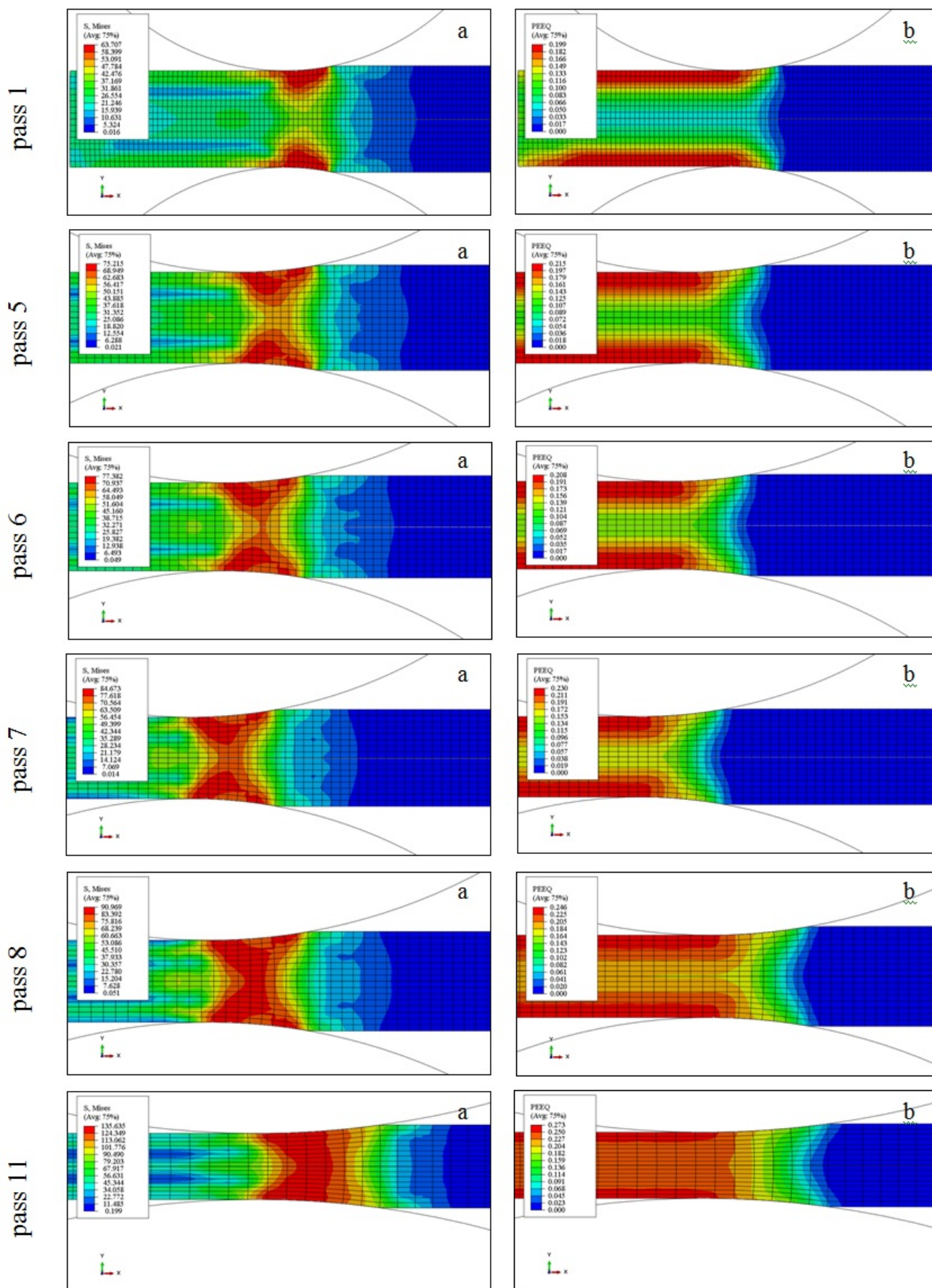
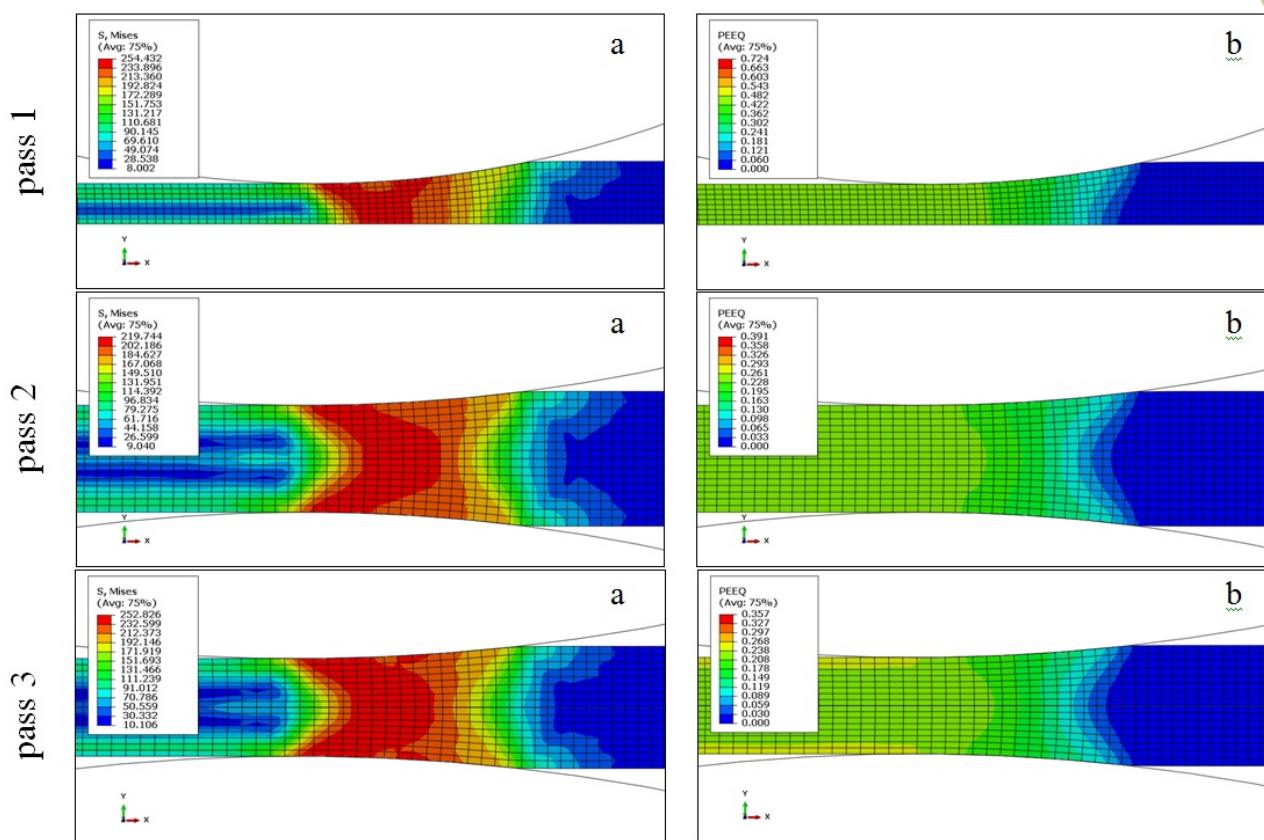


Fig. 4. The results of calculations of the equivalent stress fields (a) and equivalent plastic strain (b) in the passes at mill 3170



**Fig. 5. The results of calculations of the equivalent stress fields (a) and equivalent plastic strain (b) in the passes at rolling mill 1780 (Steckel)**

### 3.2.2. The Analysis and Discussion

The results of calculations in the passes obtained by the FE simulation have been compared to the actual results of coils rolling with dimensions of 15 mm × 1500 mm, of steel grade S355JR+AR. Additionally, in order to identify deviations associated with the fixation of the actual rolling performance, similar calculations have been performed using the improved analytical model of the rolling process [6]. Comparison of the calculations results of temperature and rolling force is given in Table 7.

On the basis of comparative calculations it has been established that the obtained deviations of the rolling force between the two methods of calculation and the actual data have comparable results and a similar trend of changes in the passes, Fig. 6. The average value of the obtained deviations does not exceed 1.54 % and -1.77 % and indicates the high accuracy of the obtained calculations results by both calculation methods.

The analytical checking calculation of the change in the temperature of the strip along the passes, used in the mathematical modeling, confirmed the presence of significant deviations in the actual temperatures during the roughing rolling, which may occur due to the location of technological pyrometers and the presence of steam.

Table 7

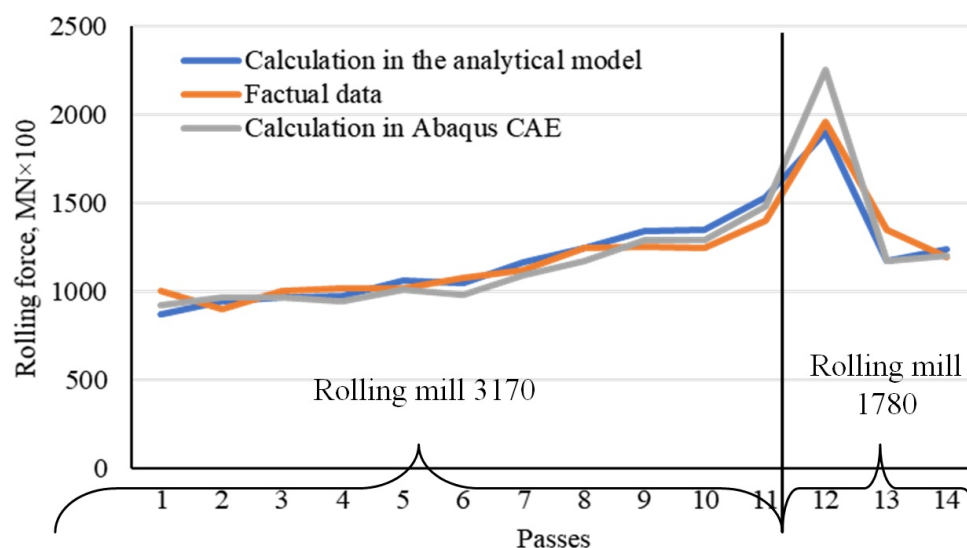
**Comparison of actual results of coils rolling with dimensions of 15 mm × 1500 mm produced of steel grade S355JR+AR at the Steckel mill with the results of calculations**

| Rolling mill                          | Pass | H, [mm] <sup>1</sup> | h, [mm] <sup>2</sup> | Reduction, [%] | Factual data         |                         | Calculation in the analytical model |                         | Calculation in Abaqus CAE | Deviation of calculations of rolling force, % |                          |
|---------------------------------------|------|----------------------|----------------------|----------------|----------------------|-------------------------|-------------------------------------|-------------------------|---------------------------|---|--------------------------|
|                                       |      |                      |                      |                | t, [°C] <sup>3</sup> | Rolling force, [MN×100] | t, [°C] <sup>3</sup>                | Rolling force, [MN×100] | Rolling force, [MN×100]   | Abaqus from the fact                          | Analytical from the fact |
| Two-high rolling mill 3170            | 1    | 221.3                | 200.49               | 9.40           | 1090                 | 1007                    | 1200                                | 867.78                  | 923.42                    | 8.30  | 13.83                    |
|                                       | 2    | 200.49               | 178.82               | 10.81          | 1068                 | 904                     | 1194                                | 946.42                  | 970.29                    | -7.33   | -4.69                    |
|                                       | 3    | 178.82               | 158.36               | 11.44          | 1068                 | 1000                    | 1187                                | 965.31                  | 963.11                    | 3.69  | 3.47                     |
|                                       | 4    | 158.36               | 139.55               | 11.88          | 1044                 | 1017                    | 1179                                | 970.42                  | 943.00                    | 7.28  | 4.58                     |
|                                       | 5    | 139.55               | 120.54               | 13.62          | 1073                 | 1015                    | 1169                                | 1060.42                 | 1011.41                   | 0.35  | -4.47                    |
|                                       | 6    | 120.54               | 103.88               | 13.82          | 1023                 | 1077                    | 1158                                | 1048.15                 | 981.68                    | 8.85  | 2.68                     |
|                                       | 7    | 103.88               | 87.23                | 16.03          | 1055                 | 1121                    | 1144                                | 1163.62                 | 1088.26                   | 2.92  | -3.80                    |
|                                       | 8    | 87.23                | 71.81                | 17.68          | 1009                 | 1243                    | 1127                                | 1243.94                 | 1174.54                   | 5.51  | -0.08                    |
|                                       | 9    | 71.81                | 57.87                | 19.41          | 1027                 | 1254                    | 1105                                | 1341.91                 | 1291.21                   | -2.97   | -7.01                    |
|                                       | 10   | 57.87                | 46.82                | 19.09          | 1027                 | 1246                    | 1076                                | 1350.15                 | 1288.40                   | -3.40   | -8.36                    |
|                                       | 11   | 46.82                | 37.16                | 20.63          | 1041                 | 1397                    | 1037                                | 1532.49                 | 1484.29                   | -6.25   | -9.70                    |
| Average                               |      |                      |                      |                |                      |                         |                                     |                         |                           | 1.54  | -1.23                    |
| Fore-high rolling mill 1780 (Steckel) | 12   | 37.16                | 23.95                | 35.55          | 999                  | 1957                    | 999                                 | 1900.98                 | 2253.24                   | -15.14  | -2.86                    |
|                                       | 13   | 23.95                | 18.98                | 20.75          | 958                  | 1351                    | 973                                 | 1173.79                 | 1169.96                   | 13.40   | 13.12                    |
|                                       | 14   | 18.98                | 15.17                | 20.07          | 920                  | 1195                    | 931                                 | 1236.66                 | 1202.42                   | -0.62   | -3.49                    |
| Average                               |      |                      |                      |                |                      |                         |                                     |                         |                           | 0.38  | -1.77                    |

<sup>1,2</sup> thickness before and after the pass, mm

<sup>3</sup> temperature before pass

Thus, the legitimacy of application of analytically calculated rolling temperatures for FE simulation has been confirmed.



**Fig. 6. Changes in the rolling force in passes according to various methods of calculation**

It is known that the average pressure when rolling is the weigh-averaged value between the stress that appears in individual layers throughout the thickness of the semi-rolled product when rolling and the stress resulted from the influence of processes outside the contact deformation. Based on the results of mathematical modeling, the levels of equivalent stress on each layer in the deformation zone have been determined, the processing of which in Excel allows to determine the value that is comparable to the average pressure when rolling. Based on this fact, and the results of analytical calculations at the roughing stage of rolling, we can determine the beginning of the formation of a continuous layer of equivalent stress during roughing rolling, i.e. the beginning of the penetration of deformation throughout the entire thickness of the semi-rolled product. The results of the calculations are given in Table 8. The intersection between the deviation curve between the maximum level of the equivalent stress ( $S$ ) and the average pressure when rolling and the curve of variation of the reduction along the passes (built within the experimental limits) is the beginning and is the corresponding condition of the deformation penetration throughout the entire thickness of the semi-rolled product at roughing rolling at rolling mill 3170, Fig. 7.

Thus, it has been determined that the beginning of the continuous layer formation of the equivalent stress during the roughing rolling, and accordingly the beginning of the penetration of deformation throughout the entire thickness of the semi-rolled product occurs in pass 6 under conditions of engineering strain equal 0.14 (reduction 14 %). The change of the deviation in the passes from positive to negative values can be explained as the process of balancing between the increase of the



equivalent stress layer in the deformation zone and the decrease, in comparison, of the influence outside the contact deformation.

Table 8

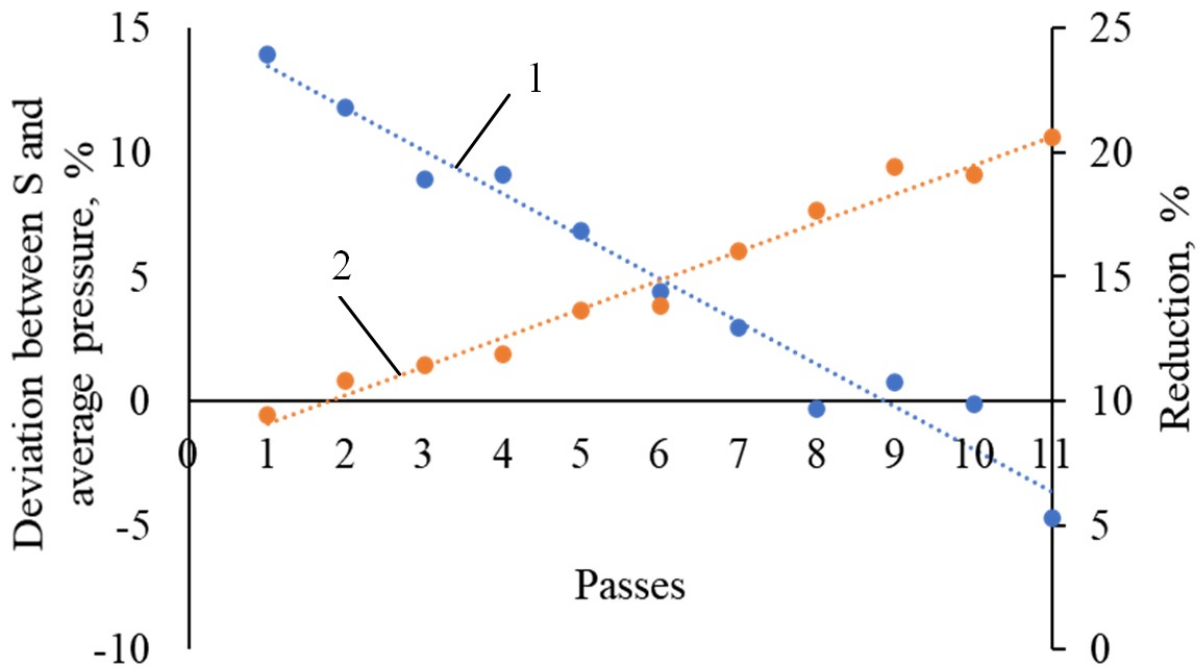
**The calculation results to determine the beginning of the formation of a continuous layer of equivalent stress during the roughing rolling at mill 3170**

| Parameter   | The value of the parameter by number of passes |       |       |       |       |       |       |       |        |        |        |
|---|--|-------|-------|-------|-------|-------|-------|-------|--------|--------|--------|
|   | 1  | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9      | 10     | 11     |
| Pass  |  |       |       |       |       |       |       |       |        |        |        |
| Average pressure when rolling, [MPa] <sup>1</sup> | 54.80  | 58.57 | 61.48 | 64.46 | 70.06 | 73.98 | 82.15 | 91.26 | 103.54 | 117.01 | 142.04 |
| Maximum level of equivalent stress, S, [MPa]      | 63.71  | 66.42 | 67.50 | 70.94 | 75.22 | 77.38 | 84.67 | 90.97 | 104.30 | 116.85 | 135.64 |
| Deviation between S and average pressure, [%]     | 13.98  | 11.82 | 8.92  | 9.14  | 6.85  | 4.40  | 2.98  | -0.32 | 0.73   | -0.13  | -4.72  |
| Reduction, [%]                                    | 9.40   | 10.81 | 11.44 | 11.88 | 13.62 | 13.82 | 16.03 | 17.68 | 19.41  | 19.09  | 20.63  |

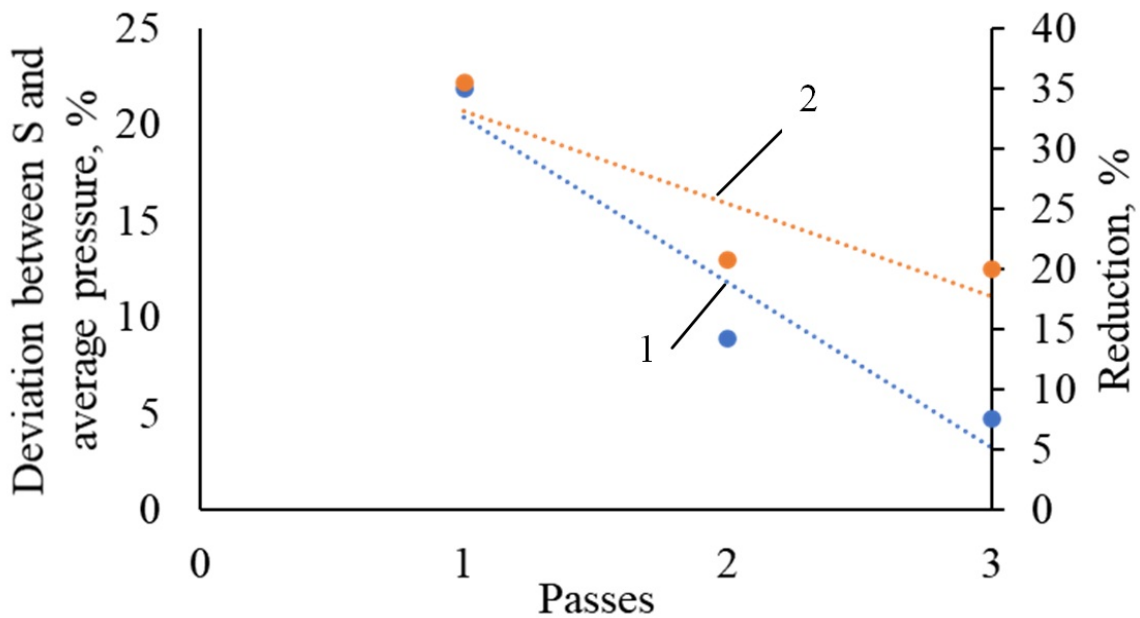
<sup>1</sup> calculated using the analytical model

In the finishing rolling at the Steckel mill, the deformation that occurs is sufficient and penetrates the entire thickness of the rolled product. Accordingly, the deviation curves of the deviation between the maximum level of equivalent stress and the average pressure when rolling and the curve of the reduction change do not intersect, Fig. 8.

Based on the obtained results of the simulation of the rolling process at the Steckel mill by the FEM the line of the beginning of the deformation penetration through the entire thickness of the semi-rolled product during the roughing rolling of steel grade S355JR+AR has been established, which is equal reduction to 14 %. In the case of finishing rolling along all passes, in the conditions of quasi-stationary temperature distribution at the Steckel mill the deformation that occurs is sufficient and penetrates the entire thickness of the rolled product. This condition and the corresponding dynamics are mostly related to the thickness of the semi-rolled product during the finishing rolling. The obtained results allow to control the processes of the internal quality and the set of rolled products properties that are to be obtained by developing appropriate technological schedules taking into account the strains through the thickness of the rolled product.



**Fig. 7. Determination of the beginning and conditions of the deformation penetration through the thickness of the semi-rolled product during the roughing rolling at mill 3170 based on the deviation curves between the maximum level of the equivalent stress and the average pressure when rolling (1) and the curve of variation of the reduction (2)**



**Fig. 8. Determination of the state of the deformation penetration through the thickness of the semi-rolled product during the finishing rolling at mill 1780 on the deviation curves between the maximum level of the equivalent stress and the average pressure when rolling (1) and the curve of variation of the reduction (2); passes 1, 2 and 3 are passes 12, 13 and 14, respectively**



### 3.3. Application for Improving the Rolling Process Modes

As a result of calculation of the rolling force and the temperature by each pass, there has been made an estimation of errors between the actual and calculated data, the results are shown in the Table 9.

**Table 9**

**Errors between the actual and calculated data on the product mix under examination**

| Mill              | Parameter     | Calculation error, [%] |           |           |           |
|-------------------|---------------|------------------------|-----------|-----------|-----------|
|                   |               | Heat code              | 81518     | 83270     | 83749     |
|                   |               | Coil section, [mm]     | 15 x 1500 | 12 x 1500 | 10 x 1500 |
| 3170              | Temperature   | average                | -9.11     | -9.06     | -8.27     |
|                   |               | minimum                | -13.2     | -15.71    | -14.7     |
|                   |               | maximum                | 0.38      | 0.96      | 1.81      |
|                   | Rolling force | average                | 0.8       | 5.7       | 0.5       |
|                   |               | minimum                | -16.0     | -3.6      | -13.6     |
|                   |               | maximum                | 8.8       | 15.5      | 9.5       |
| 1780<br>(Steckel) | Temperature   | average                | -0.92     | 0.03      | 0.003     |
|                   |               | minimum                | 0         | 0.22      | -0.205    |
|                   |               | maximum                | 1.57      | 0.31      | 0.22      |
|                   | Rolling force | average                | -4.89     | 6.59      | -2.73     |
|                   |               | minimum                | -15.1     | -5.6      | -12.94    |
|                   |               | maximum                | 3.37      | 20.9      | 12.89     |

Based on the calculation results for rolling parameters and errors, the following should be noted:

- at the mill 3170, significant deviation of the actual temperature from the calculated one is due to errors of the actual measurements, which could be affected by the water remaining on the surface of the feed after descaler or cooling of mill rolls. In this case, calculated and actual temperatures at the end of rolling at the stand 3170 have least errors, which are 0.38%, 0.96% and 0.39% for the coils with a thickness of 15mm, 12mm and 10mm, respectively. The calculated rolling force at the stand 3170 has a similar dynamics with actual data, which also confirms the correctness of the calculated temperatures.

- at the mill 1780, error in the temperature calculation is within the range from 0% to 1.57%, which is a reasonably satisfactory result, taking into account the influence of the equipment being used, in particular furnace coils. The error obtained when calculating the rolling force in the first pass for the coils with a thickness of 12mm and 10mm is related to actually higher metal temperature before the mill than



that measured after descaler.

Thus, the mathematical model of the rolling process can be used for the technology design at the Steckel mills. The resulting calculation errors due to the influence on the actual indicators of technological factors do not deteriorate the value of the developed model, and can be reduced by increasing the accuracy of measurements (temperatures) by adjusting their control points, for example, by the method [46].

## **Conclusions**

1. The research of the processes that occur in the deformation zone during the rolling process has been performed. The study of hot rolling processes at the Steckel mill by means of the FE simulation in the Abaqus CAE system has been performed on the example of the coils production with dimensions of 15 mm × 1500 mm made of structural steel grade S355JR+AR, according to EN 10025-2.

2. Based on the modeling results, the distribution of stress and strain fields along the passes has been obtained. Also, the power parameters of the rolling process have been calculated. The comparison of power parameters obtained by the FEM and calculated by the analytical method with the actual data on the results of coils rolling with dimensions of 15 mm × 1500 mm made of structural steel grade S355JR+AR at the Steckel mill has been performed. The average value of deviations does not exceed 1.54 % and -1.77 %, respectively, which proves the high accuracy of the results obtained by both methods of calculation.

3. For the first time, based on the obtained results of the rolling process simulation at the Steckel mill by the FEM the line of the beginning of deformation penetration through the entire thickness of the semi-rolled product during the roughing rolling of steel grade S355JR+AR has been determined, and it is equal to the reduction of 14 %, that corresponds to pass 6.

4. It has been established that during finishing rolling, through all passes, in the conditions of quasi-stationary temperature distribution at the Steckel mill, the deformation that occurs is sufficient and penetrates the entire thickness of the rolled product.

5. The results obtained by the FE simulation method allow to control the internal quality processes and the set of rolled product properties that need to be obtained by developing appropriate technological schedules taking into account the penetration of deformation through the entire thickness of the rolled product. The obtained results can be used to develop hot rolling technology (with one or more stages of roughing



rolling) at other types of mills and complexes of basic equipment with similar technological parameters.

6. In the paper, there has been made a verification of the developed model based on actual data obtained at the mills 3170 and 1780 (Ferriera Valsider SpA). When simulating rolling temperature conditions, an average error was within the range from 8.27 to 9.11% at the mill 3170 and from 0.003% to -0.92% at the mill 1780. When simulating rolling force, an average error was within the range from 0.5% to 5.7% at the mill 3170 and from -4.89 to 6.59% at the mill 1780.

7. There have been determined influence on the measurement of the pre-treatment temperature for the feed processing by descaler, which results in significant errors compared to the calculation results.

8. The equation has been obtained and the comparison of calculated stands stiffness has been made at the mill 3170 and 1780.

9. The developed model can be used for the rolling technology design at the Steckel mills.



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