The study of the thermal state of the metal in the production of the hot rolled strips in «Deform 3D»

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Abstract. The mathematical model of the thermal state of the sheet metal has been developed, taking into account radiation heat exchange and convection between the metal surface and the environment, the impact of descaling, heat transfer at the contact of metal with rollers, and also the heating of the metal due to plastic deformation. The model uses the results of mechanical tests obtained on the installation of the Gleeble 3800 under plane strain compression. Simulation of the rolling process is performed in the software complex «Deform 3D». The results of mathematical modeling adequately reflect the study of the thermal state of the metal produced in a sheet rolling shop. The model can be used to study the thermal state of the metal in the hot rolling production of high-quality steel grade.

1. Introduction
At the present moment the production of flat products is held to much higher standards in regards to the quality of products, particularly structure and mechanical properties. It is possible to satisfy these requirements by organization of control and management structure formation and properties of metal in the line of the mill [1].

In the production of hot rolled products special attention is given to the temperature regime of rolling, because this is one of the basics of achieving the stability of mechanical properties on the length and width of rolled strips [2-4]. The microstructure and mechanical properties of hot rolled strip steel depend on the value of the reduction in the last finishing stands, and the temperature depends on the temperature and speed of rolling. In order to obtain a homogeneous structure, rolling must be finished in the area of the χ-phase (structure-austenite), i.e. when the temperature of the end of rolling is higher at the point Ar3 [5], the relative reductions in the last stands of the finishing group must be no less that 10 %. At present time, the prediction of the thermal state of the metal, starting with the metal casting at the continuous casting machine and ending with the output of the finished product from the rolling mill, possible thanks to mathematical modeling with using modern computer systems. This is especially important, when building of new rolling equipment and the reconstruction of existing, as well as in the improvement of technologies of sheet rolling production, aimed at resource and energy saving.

The purpose of the work is to develop a modular mathematical model, which can be applied to any hot-rolled steel production technology and to study the thermal state of the metal in the production of hot-rolled steel at casting and rolling complexes, taking into account the modern requirements for the quality of the finished product.
2. Material and mathematical description

When creating a mathematical model of the thermal state of the workpiece throughout the rolling process, the following assumptions were taken into account:

- the strip material is isotropic and homogeneous;
- in the initial time the slab temperature is constant;
- the rolling process is symmetrical, because was modeled of ½ of the height of the workpiece;
- the temperature field along the length and width of the strip is not consider;
- the heat flux along the axes of symmetry do not exist.

The spatiotemporal temperature distribution of the metal was described with use non-stationary heat conduction equation, taking into account radiation heat exchange and convection between the metal surface and the environment, the impact of descaling, heat transfer at the contact of metal with rollers, and also the heating of the metal due to plastic deformation [6-7]:

\[
\rho(T)c(T)\frac{\partial T}{\partial \tau} = \lambda(T) \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q_v(x, y, z, \tau),
\]

(1)

where \(\rho\) – density; \(c\) – heat capacity; \(T\) – temperature; \(\tau\) – time; \(\lambda\) – thermal conductivity; \(Q_v\) – heat generation during plastic deformation.

The modeling was conducted for steel grade DIN-C15, its chemical composition is presented in table 1. Thermophysical properties of steel are specified by data [8].

| Table 1. The chemical composition of steel grade DIN-C15 (%) [9]. |
|---------------------------------------------------------------|
| C    | Mn | Si  | P   | S   | Cr  | Ni  | Cu  | As  | N   |
| 0.15 | 0.45 | 0.17 | 0.018 | 0.018 | 0.1 | 0.125 | 0.15 | 0.05 | 0.007 |

For modeling of rolling process curves of the dependence of flow stress of metal from true strain were used, obtained of laboratory tests under plane strain compression on the installation of the Gleeble 3800 at Czestochowa University of Technology (Poland). Researches were conducted at temperatures of deformation from 800 to 1300 °C and strain rate from 0.1 to 170 1/s (figure 1) on samples in the parallelepiped form with dimensions of 10x15x20 mm, the width of the deformation zone was 5 mm.

The values of the true strain and stress of the metal flow during the plane strain compression tests were calculated using the formulas [10]:

\[
\varepsilon = \frac{2}{\sqrt{3}} \ln \left| \frac{h}{h_0} \right|,
\]

(2)

\[
\sigma = \frac{\sqrt{3}}{2} \frac{F}{w b},
\]

(3)

where \(h\ \text{and} \ h_0\) – the initial and final height of sample; \(F\) – force; \(w\) – the width of the deformation zone; \(b\) – the length of the sample.

The obtained experimental data were corrected and added to the preprocessor of the program «Deform 3D».

3. The study of the thermal state of the metal in «Deform 3D»

3.1. Adaptation of the model of the thermal state of the metal in line of hot rolling mill

Adaptation of the model of the thermal state of the metal was the selection of the coefficients, used in the simulation for order to obtain adequate results.

The mathematical modeling of the thermal state of metal in hot rolling mill is performed by using the module «Shape rolling» and solver «ALE rolling» of the software complex «Deform 3D». The composition of the equipment adopted in the simulation corresponds to the mill 2000 of PAO «NLMK» [11].
Figure 1. Curves of the dependence of flow stress of metal from true strain for steel grade DIN-C15 (T = 900, 1000, 1100, 1200 °C; \( \dot{\varepsilon} \)=0.1, 1, 10, 170 1/s).

The movement of the workpiece in line of rolling mill was modeled in the form of successive operations. Every operation is represented as standalone module, which carries the information about the object or objects and the nature of the distribution of boundary conditions. In modeling of rolling process in line of mill used three main modules:

- module «heat transfer», describing the heat exchange between workpiece and environment;
- module «water descaling», describing the effect of high-pressure water on the upper surface of the workpiece;
- module «rolling», describing the interaction of the workpiece with the working roll of the rolling mill.

Knowing the composition and characteristics of the equipment of the rolling complex, as well as the initial data about workpiece, creates a computational scheme of the technological chain, based on the purpose of obtaining the finished product. Information about the studied object was introduced at the initial stage of modeling, which later was recorded in the «DEFORM Database file» at regular intervals. When a new module was connected, the data was loaded from the last step of previous operation (figure 2). In consequence, the chain of operations is receive, and information about the object and all its changes is stored all through the modeling process.

Figure 2. Example of information transfer, using the modules «heat transfer-water descaling-heat transfer-rolling» in «Deform 3D».
The temperature parameters were calculated according to the modes shown in the tables 2-3, using a reversing rolling in the 1st stand of the roughing group. The height of the slab at the entry to the 1st stand is 250 mm, the height of the strip at the exit of the 12th stand is 4 mm. In the simulation the distribution of the temperature field along the length and width of the investigated object is not considered, therefore, was modeled on the scale of ½ of the height of the workpiece with a width of 10 mm and a length of 400 mm, breaking the object at the initial stage with 10000 elements, using «brick mesh».

### Table 2. The parameters of rolling for roughing stands.

| № stand | 1 | 1 | 1 | 2 | 3 | 4 | 5 |
|---------|---|---|---|---|---|---|---|
| h₀, mm  | 218.00 | 184.70 | 149.80 | 119.90 | 78.10 | 48.50 | 30.00 |
| ε, %    | 12.80 | 15.28 | 18.90 | 19.96 | 34.86 | 37.90 | 38.14 |
| ν, m/s  | 1.00 | 1.00 | 1.00 | 1.50 | 2.00 | 2.50 | 3.20 |
| T_roll, °C | 90.00 | 90.00 | 90.00 | 90.00 | 85.00 | 85.00 | 80.00 |

### Table 3. The parameters of rolling for finishing stands.

| № stand | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------|---|---|---|---|----|----|----|
| h₀, mm  | 22.23 | 15.46 | 11.57 | 8.45 | 6.16 | 4.78 | 4.00 |
| ε, %    | 25.90 | 30.45 | 25.16 | 26.97 | 27.10 | 22.40 | 16.32 |
| ν, m/s  | 1.08 | 1.55 | 2.07 | 2.84 | 3.90 | 5.02 | 6.00 |
| T_roll, °C | 50.00 | 48.00 | 48.00 | 44.00 | 37.00 | 35.00 | 35.00 |

The following data were taken for calculation:
- the convection coefficient «strip-air» is 10 W/(m²·K), the convection coefficient «strip-water» is 13000 W/(m²·K), the convection coefficient «strip-roll» is 16000 W/(m²·K) [12];
- the temperature of slab at output from furnace is homogeneous and is 1250 °C;
- the environment temperature is 20 °C for air and 30 °C for water;
- the surface temperatures of the working rolls are specified by data [13].

The results are presented graphically in figures 3-4.

![Figure 3. Temperatures in roughing stands of the hot rolling mill.](image-url)
The study of the thermal state of the metal was considered by the example of the casting and rolling unit Danieli QSP. The mathematical model of the thermal state of the metal in the production of hot rolled products at the casting and rolling unit [14] in the modes of coil-to-coil and endless rolling.

The mathematical modeling of the thermal state of metal in hot rolling mill is performed by using the module «Shape rolling» and solver «ALE rolling» of the software complex «Deform 3D». The temperature parameters were calculated according to the modes shown in the tables 4-5.

Table 4. The parameters of rolling in line of the casting and rolling unit: coil-to-coil rolling mode.

| № stand | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| h_s, mm | 69.50 | 37.50 | 18.00 | 10.70 | 7.40 | 5.70 | 4.60 | 4.00 |
| ε, %    | 36.82 | 46.04 | 52.00 | 40.56 | 30.84 | 23.65 | 18.58 | 13.04 |
| v, m/s  | 0.50 | 0.60 | 1.14 | 2.02 | 3.24 | 4.25 | 5.22 | 6.00 |
| D_rol, mm | 950.00 | 950.00 | 830.00 | 830.00 | 830.00 | 640.00 | 640.00 | 640.00 |
| T_rol, °C | 90.00 | 85.00 | 80.00 | 50.00 | 48.00 | 44.00 | 37.00 | 35.00 |

Table 5. The parameters of rolling in line of the casting and rolling unit: endless rolling mode.

| № stand | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| h_s, mm | 69.50 | 37.50 | 18.00 | 10.70 | 7.40 | 5.70 | 4.60 | 4.00 |
| ε, %    | 36.82 | 46.04 | 52.00 | 40.56 | 30.84 | 23.65 | 18.58 | 13.04 |
| v, m/s  | 0.40 | 0.50 | 0.80 | 1.00 | 1.45 | 1.90 | 2.33 | 2.68 |
| D_rol, mm | 950.00 | 950.00 | 830.00 | 830.00 | 830.00 | 640.00 | 640.00 | 640.00 |
| T_rol, °C | 90.00 | 85.00 | 80.00 | 50.00 | 48.00 | 44.00 | 37.00 | 35.00 |

Figure 4. Temperatures in intermediate table and finishing stands of the hot rolling mill.

In the production of hot rolled strip surface is characterized by a significant decrease in temperature due to the influence of the cooling effect of the water descaling, as well as in contact of metal with rolls. However, outside the zones of intensive cooling, there is a redistribution of heat due to internal sources and an increase in surface temperature during the passage of strip between rolling stands. Additionally, the temperature increase is observed in the deformation zone due to plastic deformation and the work of the contact friction forces.

The surface temperature at the exit from 5th stand, obtained in the simulation, is about 1000 °C, the surface temperature at the exit from 12th stand is 864 °C.

3.2. Model of the thermal state of the metal in the production of hot rolled products at the casting and rolling unit

The study of the thermal state of the metal was considered by the example of the casting and rolling unit Danieli QSP-DUE [14] in the modes of coil-to-coil and endless rolling.

The mathematical modeling of the thermal state of metal in hot rolling mill is performed by using the module «Shape rolling» and solver «ALE rolling» of the software complex «Deform 3D». The temperature parameters were calculated according to the modes shown in the tables 4-5.
The height of the slab at the exit of casting machine is 110 mm, the height of the strip at the exit of the 8th stand is 4 mm. In the simulation the distribution of the temperature field along the length and width of the investigated object is not considered, therefore, was modeled on the scale of ½ of the height of the workpiece with a width of 10 mm and a length of 400 mm, breaking the object at the initial stage with 12350 elements, using «brick mesh».

The following data were taken for calculation:
- the convection coefficient «strip-air» is 10 W/(m²·K), the convection coefficient «strip-water» is 15000 W/(m²·K), the convection coefficient «strip-roll» is 16000 W/(m²·K) [12];
- the temperature of slab at output from tunnel furnace is homogeneous and is 1150 °C;
- the environment temperature is 20 °C for air and 30 °C for water;
- the surface temperatures of the working rolls are specified by data [1, 13];
- the diameters of rolls are specified by data [14, 15].

For the comparative analysis of the modes of coil-to-coil and endless rolling in the postprocessor of the program «Deform 3D» in the section «State Variables» for each experience, the results of the average temperature of the metal were obtained, using the option «Histogram». Temperatures were recorded in separate sections of the casting and rolling unit (figure 5).

![Figure 5. Average temperature along the length of the casting and rolling unit.](image)

In the production of hot rolled strips during coil-to-coil rolling mode a gradual fall of the average temperature in line of the casting and rolling unit is derived. Due to the optimal choice of deformation and temperature-speed modes of rolling, regardless of the casting speed at the casting machine and the thickness of the finished strip, the obtaining high-quality products with the necessary properties without using induction heating of the metal on the intermediate table is possible.

During endless rolling mode a more intense fall of temperature of the metal is derived, starting from the tunnel furnace and ending with the exit from the last stand of the roughing group and less intensively is on the intermediate table. Using of induction heating before the finishing stands compensated these losses and contributed to the required end temperature of the rolling. It follows that the production of endless rolling mode confronts with the problem of maintenance the temperature in line of the casting and rolling unit, but with the rational use of existing equipment and the choice of optimal technology of production contributes to the stable operation of all unit and the production of high quality products.
4. Conclusion

A mathematical model of the thermal state of the metal in conditions of traditional casting and rolling complex and joint casting and rolling unit was developed, taking into account radiation heat exchange and convection between the metal surface and the environment, the impact of descaling, heat transfer at the contact of metal with rollers, the heating of the metal due to plastic deformation, and also the heating in coverage area of induction heating (in the production of hot rolling products at casting and rolling unit, using endless rolling mode). The model is adapted to the conditions of existing production.

Based on the study of the thermal state of the metal obtained graphs of temperature changes of the surface and center of the metal at the traditional casting and rolling complex and combined casting and rolling unit.

The graphs of changes of average temperature of the metal along the length of the unit in the production of hot rolled strips by coil-to-coil and endless rolling modes at the casting and rolling unit is presented.

The using of «Deform 3D» favor the study of technological processes in full measure to the high accuracy of the results, and also the ability to simulate complex geometric objects and the use of mixed boundary conditions for solutions of a specific problem.

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