Development of mathematical models and methods for calculation of rail steel deformation resistance of various chemical composition

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Abstract. Using the device of the complex “Gleeble System 3800” the physical experimental studies of deformation resistance of chrome rail steel at different thermo-mechanical deformation parameters were carried out. On the basis of mathematical processing of experimental data the statistical model of dependence of the rail steel deformation resistance on the simultaneous influence of deformation degree, rate and temperature, as well as the steel chemical composition, was developed. The nature of influence of deformation parameters and the content of chemical elements in steel on its resistance to plastic deformation is scientifically substantiated. Verification of the adequacy of the proposed model by the comparative analysis of the calculated and actual rolling forces during passes in the universal rail-and-structural steel mill JSC “EVRAZ Consolidated West Siberian Metallurgical Plant” (“EVRAZ ZSMK”) showed the possibility of its use for development and improvement of new modes of rails rolling.

1. Introduction

Steel resistance to plastic deformation (deformation resistance) is one of the most important characteristics of metal strength during its forming in the rolling process. According to the accepted concepts by deformation resistance the stress intensity is understood sufficient for the plastic deformation of metal under specified deformation conditions [1-5].

Deformation resistance directly determines the power parameters of rolling as the magnitude of this parameter conditions the metal pressure on rollers, and as a result the rolling enforcement. Thus, use of incorrect data on the magnitude of deformation resistance during designing the rolling modes might lead either to overloads of the main equipment (in the case of underestimating of deformation resistance in comparison with its real values) or to underutilization of the equipment and, as a consequence, to the decrease in mill productivity (using the overstated deformation resistance values in relation to the actual values). One of the most important tasks in the development and improvement of rolling modes on the operating and especially on the newly commissioned rolling mills is to obtain
reliable data on the magnitude of the steel resistance to plastic deformation under specified conditions of rolling.

Analysis of the literature shows that the following physical and chemical parameters influence the deformation resistance during rolling: thermo-mechanical parameters of deformation (temperature, rate and degree of deformation) and the chemical composition of steel.

Currently used methods for calculating the deformation resistance are based on the presence of the predetermined basic value of this parameter under standard conditions (temperature, rate and degree of deformation). Calculation of the deformation resistance for the specific conditions of rolling in this case is done by multiplying the basic value of deformation resistance by the thermo-mechanical coefficients, values of which are determined experimentally.

A significant disadvantage of this group of methods is the limited field of their application – they provide with the adequate to the actual values results only for the increasing curves, characterizing the dependence of the steel resistance to plastic deformation on the degree of deformation [6, 7]. Furthermore, in the literature there is information about the basic value of deformation resistance only for a limited number of steel grades [8]. In particular for rail steels such data are not available.

The most reliable way to obtain information about the true values of deformation resistance for today is the experimental studies by the methods of hot mechanical testings of samples for tension, torsion or compression. The first two methods have significant drawbacks. When performing hot pulling test even at relatively small deformations (20-30%) there is a high degree of deformation heterogeneity and a change in the deformation rate in the metal volume takes place, which is explained by formation of a web in the sample during testing.

Method of hot torsion is characterized by a considerable deformation heterogeneity over the cross-section: the degree and rate of deformation vary from the maximum value on the surface to the minimum (up to zero) values of true deformation in the center (along the rotation axis) of the cylindrical sample.

The advantage of the compression test is the possibility to apply high deformation degrees. Although it should be noted that at the degree of deformation more than 60-70% the sample takes “barrel” shape, which significantly increases inaccuracy of the research. This phenomenon is due to the fact that during the upset of the metal billet the metal sliding on the contact surface is delayed by friction forces.

Thus, nowadays, in order to develop a method for calculating the deformation resistance experimental studies of deformation resistance of rail steel should be performed. The most preferred method of mechanical testing of samples during the studies is a hot compression.

2. Experimental research

Experimental study of deformation resistance of rail steel E78KhSF was carried out using the apparatus “Hydrawedge II”, which is one of four possible changeable modules for the complex of physical modeling of thermo-mechanical processes “Gleeble System 3800” [9]. “Hydrawedge II” consists of the following subsidiary devises (Figure 1): instruments for control of temperature, force, displacement; the mobile module for creation of an artificial atmosphere in the working chamber; deforming bars with a water cooling system, necessary for elimination of the undesirable effect of heating on tools and measuring instruments.
Figure 1. Module scheme of “Hydrawedge II” for the complex of physical modeling “Gleeble System 3800”.

During hot compression tests rectangular and cylindrical samples were used, obtained from cast billets of steel produced by JSC “EVRAZ Consolidated West Siberian Metallurgical Plant” (“EVRAZ ZSMK”).

Testing mode included the following steps (Figure 2): heating of the template in vacuum at the rate 5°C/sec to a temperature of 1200 °C for 240 sec; isothermal exposure for 600 sec at 1200 °C; steel cooling-down to deformation temperature at 10 °C/sec; deformation at a predetermined temperature; steel cooling at rates from 50 °C/sec to 10 °C/sec. Samples were deformed at rates 0.1, 1 and 10 sec-1 with temperatures 1150, 1100, 1050, 1000, 950 and 900 °C.

Figure 2. Test scheme of rail steel samples E78KhSF.
3. Results and discussion

Generalization and mathematical processing of the experimental characteristic curves, the examples of which are shown in Figure 3, allowed us to obtain a statistical model of dependence of deformation resistance of rail steel E78KhSF on the simultaneous influence of the degree, rate and deformation temperature:

\[
\sigma = A \cdot e^{m_1 \cdot t} \cdot e^{m_2 \cdot \varepsilon} \cdot \varepsilon^{m_3} \cdot (1 + \varepsilon)^{m_4} \cdot e^{m_5 \cdot u} \cdot u^{m_6 \cdot t}
\]

where:
- \(t\) – rolling temperature, \(^\circ\)C;
- \(\varepsilon\) – deformation degree;
- \(u\) – deformation rate, sec\(^{-1}\).

Analysis of the experimental nature of dependencies (Figure 3) showed that in areas where the degree of deformation is less than 0.7 the curves have a pronounced maximum.
Figure 3. Experimental dependence of the deformation resistance of steel E78KhSF on the rate and degree of deformation (a – deformation temperature 900 °C; b – deformation temperature 1150 °C).

That is, after a certain deformation degree is achieved, in the steel in addition to the dynamic recovery and polygonization a dynamic recrystallization takes place. The indicated maximum shifts towards the increase in the deformation degree when the temperatures go up, shifts backward as the deformation rate increases. Then in the zone corresponding to the deformation degree 0.7-1.0 on some curves there is a repeated increase in deformation resistance, which is obviously conditioned by the error of the experiment due to the increased “barreling” of samples at high deformation rates.

According to the data the increase in the rolling temperature of rail steel E78KhSF steel in the range 900-1150 °C leads to a decrease in deformation resistance due to the weakening of the material bindings of particles and the creation of favorable conditions for their mutual displacement. Increase in the deformation rate within the range 0.1-10 sec$^{-1}$ on the contrary increases the deformation resistance, since in that case the hardening processes begin to prevail over the competing processes of steel softening.

As a result of the statistical analysis of the influence of steel chemical composition on the coefficients of equation (1) the regression equations in natural scale are obtained:

$$ A = 4365.4 + 691184.4365 \cdot S \quad (2) $$
$$ m_1 = -0.0033 - 0.0043 \cdot V \quad (3) $$
$$ m_2 = 0.2607 - 5.7663 \cdot P \quad (4) $$
$$ m_3 = -0.0025 + 0.00308 \cdot C + 0.00025 \cdot Mn \quad (5) $$
$$ m_4 = -0.0015 + 0.0475 \cdot P \quad (6) $$
$$ m_5 = -0.407 + 0.655 \cdot Mn \quad (7) $$
$$ m_6 = 0.0002 - 0.0012 \cdot V \quad (8) $$

where S, V, P, C, Mn – content of sulfur, vanadium, phosphorus, carbon and manganese in the steel respectively, %.

Summarizing the findings about the influence of chemical composition of rail steel E78KhSF on the coefficients of equation (2) and, consequently, on the deformation resistance, it can be stated that the increase in the content of manganese, carbon, sulfur and phosphorus in these limits increases the deformation resistance. The increase in vanadium content from 0.04% to 0.07% reduces the steel resistance to plastic deformation due to significant influence of vanadium additives even in small quantities on improvement of steel ductility.

Effects of chromium and silicon in the considered range of their variation were not found, which is consistent with data from other sources [3]. There is evidence that silicon increases the deformation resistance of steels only when its concentration is at the level of 1.5-2.0%, and for the high-carbon chromium steels (with chromium content more than 0.45%), a decisive influence on the deformation resistance has carbon but not chrome.

In order to assess the quantitative impact of changes in the content of chemical elements on the deformation resistance of chrome rail steel the computational experiment was carried out. The essence of the experiment was to do calculations of the deformation resistance of rail steel E78KhSF with different chemical composition, the variation of which was carried out under the condition of alternate change in the content of each considered chemical element and constant content of other elements. The calculation was performed for the deformation conditions, typical for rolling in roughing and finishing stands of rolling mills: $t = 1150$ °C, $u = 5$ sec$^{-1}$ (roughing stands); $t = 1050$ °C, $u = 15$ sec$^{-1}$ (finishing stands); (for both groups of stands).
According to the results of numerical experiment it was shown that the most significant influence on the deformation resistance of chrome rail steel had vanadium and sulfur (Figure 4).

\[ u = 5 \text{ sec}^{-1}; t = 1150 \, ^\circ\text{C} \]
\[ u = 15 \text{ sec}^{-1}; t = 1050 \, ^\circ\text{C} \]

**Figure 4.** Dependence of deformation resistance on the chemical composition of rail steel E78khSF (a, b – dependence of the deformation resistance on vanadium content; c, d – dependence of the deformation resistance on sulfur content).

Increase in vanadium content from 0.04 to 0.07% leads to a decrease in the deformation resistance 1.24-1.27 times (Figure 4 a, b) and increase in the concentration of sulfur from 0.005 to 0.015% causes an increase in deformation resistance by 1.14 times (Figure 4 c, d). This temperature reduction and increase of deformation rate enhances the effect of vanadium on the steel resistance to plastic deformation. The increased content of phosphorus, manganese, and carbon in the steel within the considered ranges leads to the increase in the deformation resistance up to 10%, 5% and 1% respectively.

On the basis of experimental and statistical studies the method for calculation of deformation resistance was developed, which takes into account the impact of the thermo-mechanical deformation parameters and chemical composition of steel [10, 11].

Application algorithm of this method includes the following steps:

- Calculation of the equation coefficients (1) for a given chemical composition of steel using the regression equation (2-8).
- Calculation of the actual deformation resistance values for given parameters of thermo-mechanical rolling (the degree of deformation, temperature and deformation rate) using equation (1).

In order to test the adequacy of the developed method for determining the deformation resistance of rail steels, a comparative analysis of the calculated and the actual rolling forces in passes in the first breakdown stand of the universal rail-and-structural steel mill “EVRAZ ZSMK” was performed.
During calculations of the deformation resistance two chemical compositions of steel E78KhSF were used: standard chemical composition corresponding to the average content in the melts of current production (average content values of carbon, manganese, silicon and chromium according to State Standards (GOST) R 51685-2000, vanadium content – 0.07%; sulfur and phosphorus – 0.015% for each element); chemical composition similar to the first variant except for the sulfur content and vanadium (0.04% and 0.005% respectively).

The calculation of rolling force in the box grooves and the final horizontal T groove of the breakdown stand was performed using standard methodology proposed by the authors [12]. According to the obtained data the deviations of the calculated data from the actual ones do not exceed 10% (Figure 5).

Thus, it can be concluded that the developed method for deformation resistance calculation can be used in the design of new rolling modes of rail steels. Since no significant effect on the deformation resistance of the silicon and chromium content was revealed, the field of application of this technique can be extended not only on E78KhSF steel, but also on the rail steels not alloyed with these elements, in particular E76F and E76.

![Figure 5](image.png)

**Figure 5.** Comparative analysis of the calculated and actual data for the rolling force in the breakdown stand of the universal rail-and-structural steel mill “EVRAZ ZSMK” (a – standard chemical composition of steel E78KhSF; b – E78KhSF steel with a lowered content of sulfur and vanadium).

4. **Conclusions**

Based on the experimental research of deformation resistance of chrome steel rail, conducted on the facility for physical modelling of thermo-mechanical processes “Gleeble System 3800”, a comprehensive statistical model of deformation resistance dependence on the deformation parameters (degree, rate and temperature of deformation) and steel chemical composition was developed. The nature of the influence of deformation parameters and the content of chemical elements in steel on its resistance to plastic deformation is scientifically substantiated. Verification of the adequacy of the developed model by the comparative analysis of calculated and actual rolling forces in the passes in breakdown stand of the universal rail-and-structural steel mill JSC “EVRAZ ZSMK” showed the possibility for its use in the development and improvement of new rolling modes.

5. **References**

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