Development of measures to reduce longitudinal bending of thick clad and alloyed steel plates during hot rolling

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This article investigates methods for preventing longitudinal bending of the workpiece during hot rolling of thick-plate alloyed and clad steel at an industrial plate mill. The main problem addressed is the occurrence of uncontrolled bending, which leads to geometric defects, equipment damage, and the need for premature removal of rolled plate. The key contributing factors are identified, including temperature gradients, differences in friction conditions between the upper and lower surfaces of the workpiece, and deformation asymmetry caused by various reasons (e.g., differing properties of the base and cladding layers for clad steel, different roll diameters, etc.). The study employed comprehensive analysis methods, including laboratory experiments using a Gleeble simulator and a two-high rolling mill, as well as mathematical modeling of the rolling process using the finite element method (FEM). It was found that localized cooling (e.g., descaling sprays at the mill entry and exit) has limited effectiveness due to shallow penetration depth. The most effective solution was the creation of a linear temperature gradient of 40 °C across the slab thickness during furnace heating. Industrial trials confirmed that combining gradient heating with automatic roll speed adjustment and the use of descaling sprays in the mill effectively minimizes workpiece bending without compromising the mechanical properties of the final product.
Key words: hot rolling, asymmetric rolling, high-alloy steels, clad rolled products, clad steel plate, mathematical modeling, temperature gradient, scale, finite element method, rheological properties.
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Introduction

Experience in producing alloyed steel grades on thick-plate mills shows that uncontrolled bending of workpieces can occur during rolling, sometimes leading to equipment damage or the need to remove the unfinished product from the production line.

This problem is particularly evident in the production of steel grades with high chromium and nickel content, such as the shipbuilding grade 10KhGSN2MBF. An example of the deformed workpiece is shown on **Fig. 1**.

For clad rolled products using asymmetric sandwich slabs, bending occurs due to differences in the properties of the cladding and base layers [1–3]. While eliminating bending entirely during the initial passes in the roughing stage is often impossible, controlling the process is necessary to ensure satisfactory flatness.

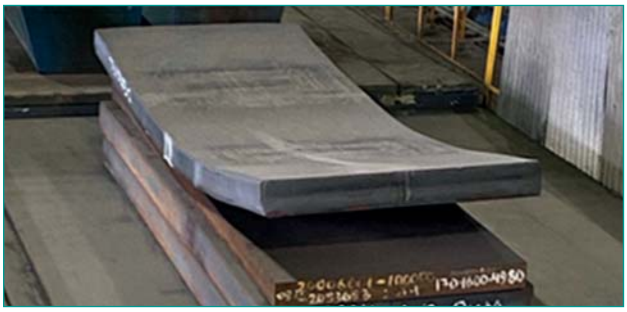

Fig. 1. Example of a deformed workpiece of alloyed steel grade 10KhGSN2MBF

The formation of longitudinal bending during the rolling of alloyed steel grades is attributed to several factors [4, 5]:

- Different heat exchange conditions on the upper and lower surfaces of the slab/workpiece. Temperature differences arise not only from “metal-to-metal” contact with the roller table but also from convective heat transfer characteristics. When rolling alloyed steels with increased resistance to deformation, the difference in properties of the steel caused by varying temperatures become significant, thereby greatly affecting the moment balancing algorithm, which will start to slow down one of the rolls, leading to the bending of the rolled product. [6–10].
- The composition of scale on alloyed steel grades can alter the friction coefficient between the workpiece surface and the roll, contributing to bending.
- Incorrect regulation of the workpiece profile [11, 12].
- Improper selection of reduction schedules and other rolling parameters [13–16].
- Geometric dimensions of the slab [17].

Modern rolling mills feature automated control systems with algorithms for adjusting bending by varying roll speeds. However, as practice shows, this measure alone is often insufficient [18]. Operators can manually adjust parameters, but rapid response is required due to the short duration of each pass (3–4 seconds). Additionally, extensive practical experience is needed to determine the required adjustments, as bending can occur under varying reduction levels, workpiece temperatures, and other conditions. Excessive adjustments may overload one of the drives and halt production.

A proactive approach is needed to avoid emergency process corrections. One solution is the use of a temperature gradient across the workpiece thickness, achievable through:

- Descaling sprays installed at the mill entry and exit – cooling the surface opposite the bend. However, this method has limited effectiveness due to shallow penetration depth as will be discussed below.
- Introducing a temperature gradient during slab heating in the furnace. This approach is the most feasible for industrial production.

The goal of this work is to develop recommendations for heating slabs/clad slabs to control bending during the rolling of alloyed steel grades and clad rolled products.

To achieve this goal, the following tasks were addressed:

1. Determining the rheological properties of the studied steels under a wide range of strains, strain rates, and temperatures using thermomechanical testing and physical modeling.
2. Developing a finite element method (FEM)-based mathematical model for the hot rolling of monolithic and clad products.
3. Conducting experiments on a DUO-300 laboratory mill.
4. Collecting data from industrial rolling cases for the product range studied.
5. Adapting the model based on industrial and laboratory rolling data.
6. Simulating rolling cases with variable friction coefficients and temperature gradients across the slab thickness.
7. Developing technological recommendations for industrial rolling.

Materials and Methods

The study investigated the deformation resistance of steel grades 09G2S, 08Kh18N10T, and 10KhGSN2MBF under various deformation parameters. The chemical composition of these steels is provided in **Table 1**.

Tests on the Gleeble 3800 were conducted using cylindrical samples (10 mm diameter, 15 mm height) at strain rates of 0.1, 1, and 10 s^{-1} and temperatures ranging from 850–1200 °C. The thermal cycle included:

- Solution treatment: Heating at the rate 0.35 °C/s to 1250 °C, holding for 30 min, and cooling at the rate >200 °C/s.
- Deformation test: Heating at the rate 5 °C/s to 1150 °C, holding for 120 s, pre-straining (ε = 0.1, strain rate = 1 s^{-1}), holding for 20 s, cooling to the test temperature at the rate 10 °C/s, and holding for 10 s before the main deformation.

Laboratory rolling was performed on a DUO-300 two-high mill at the Central Research Institute for Ferrous Metallurgy. The mill specifications: roll diameter — 300 mm; barrel length — 250 mm; maximum rolling force — 1.7 MN (170 t); maximum rolling torque — 0.061 MN·m; main drive motor power — 110 kW; rolling speed — 50–300 mm/s.

Mathematical models were developed using FEM in ANSYS, employing 8-node elements for 3D simulations without horizontal symmetry due to differences in the properties of the base and cladding layers.

Study of Material Properties Using the Gleeble System

An example of the deformation resistance test results for the studied steel grades is shown in **Fig. 2**. For steel 10KhGSN2MBF, the deformation resistance at high temperatures was 24 % higher than that of 09G2S but 14 % lower than that of 08Kh18N10T. Additionally, this steel exhibited greater sensitivity to temperature changes compared to the other two grades — its deformation resistance decreased by 10 % with a 50 °C temperature increase.

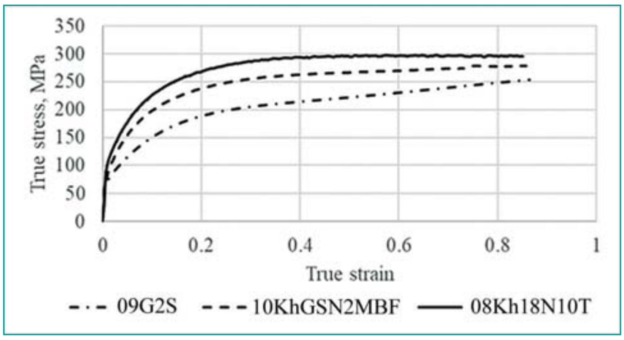

Fig. 2. Examples of stress-strain curves obtained from Gleeble testing at a strain rate of 1 s^{-1} and temperature of 900 °C

Development of Mathematical Models for Industrial and Laboratory Rolling Processes

In the study of rolling alloyed steel grades, a three-dimensional problem statement is used. The model consists of 7 bodies: pusher, two tables (before and after the stand), upper and lower rolls, symmetry plane, and workpiece (slab). All bodies except the workpiece are rigid, without mesh discretization, but with heat transfer accounted for.

For modeling the industrial workpiece in 3D, 24 thousand eight-node elements are used (with symmetry plane applied along the width). Boundary conditions are added to account for gravity. The friction coefficient between the workpiece (ferrous metal) and the roll was adopted considering

Table 1. Chemical composition of samples tested on the Gleeble simulator

	C	Si	Mn	Cr	Mo	Ni	Nb	Ti	V
08Kh18N10T	0.08	0.54	1.20	18.6	–	11.97	–	0.57	–
10KhGSN2MBF	0.085	0.24	0.49	1.06	0.106	1.91	0.04	0.01	0.03
09G2S	0.11	0.55	1.63	0.03	–	0.01	–	0.005	–

the results of laboratory experiments presented later in the article. Siebel's friction law is used.

The relationship between stresses and strains of the workpiece material is defined using an elastic-plastic material behavior model. Plastic properties are assigned based on data obtained from the Gleeble system. Elastic and thermal properties are assigned according to data from open sources [19].

In the developed model, to form a temperature gradient before rolling, the heating of the slab is simulated with different temperature setpoints for the upper and lower zones of the furnace. Then, to obtain the initial temperature field of the workpiece, a holding period is simulated in accordance with physical experiments, corresponding to the average time between slab extraction from the furnace and feeding into the stand. Between passes, a pause is simulated (time for roll reversal and workpiece feeding into the stand).

The rolling modes in the model correspond to the roughing stage modes for the specified products from 355 mm slabs on industrial plate mills.

For modeling clad rolling, a model like that described in [3] was used. For the laboratory rolling process – a model like [1]. The general views of the models are shown in **Fig. 3**.

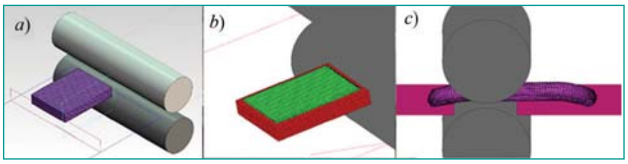

Fig. 3. General view of models: industrial hot rolling of high-alloy steels (*a*), industrial rolling of clad products (*b*), laboratory rolling (*c*)

For the industrial case, 5 rolling passes with average reduction 5 % were simulated. The workpiece thickness after the 5th pass was 260 mm, which is sufficient for evaluating the effectiveness of the developed approaches.

Since in industrial rolling the workpiece bends upward, the goal of modeling was to reproduce the bending magnitude of the workpiece similar/close to that observed at the mill (defect simulation). Then, the conditions (considered tools/methods) that produced the required bending degree were to be applied in reverse at the industrial mill to compensate for the bending.

Conducting laboratory experiments

As part of laboratory experiments, a study was conducted on the effect of scale on the change in friction conditions on the upper and lower working rollers, as well as the influence of temperature gradient on the compensation of bending.

To obtain samples with industrial scale, 6 billets (made of steel grade 10KhGSN2MBF) with dimensions of approximately 50×150×250 mm were placed on slab. The contact surface of the billets was treated with a high-temperature adhesive lubricant, which allowed the samples to remain on the surface of the slab during transportation and prevented sticking during heating. The samples and slab were then heated in a walking beam furnace of an industrial plate mill. After heating, the samples were knocked off the slabs and cooled in water. The resulting samples had thick industrial scale on one of their contact surfaces. The samples were then reheated and rolled.

According to the rolling results, it was noted that the samples placed in the stand with the industrial scale downwards exhibited significant bending in the opposite direction from the scale (a thick layer of scale at the bottom caused upward bending). The bending was also influenced by the deformation modes. When rolling with small reductions during the roughing stage, it was possible to complete all six passes. This rolling resulted in significant upward bending, making further rolling impossible (see **Fig. 4**). In the case of rolling with large reductions, only three passes of the roughing stage could be completed, and the degree of bending increased more intensively.

Since the samples were heated uniformly, the only possible reason for the bending could have been the difference in friction on the upper and lower surfaces of the rolled product. Using the laboratory mill model described above, a series of calculations were conducted to select friction coefficients to adapt the industrial model to the observed friction conditions. Even with the maximum difference in the friction coefficient (friction described by the Siebel law, with coefficients set from 0.4 to 0.8), it was not possible to achieve the bending observed in laboratory experiments.

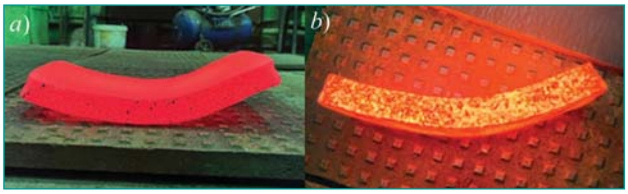

Fig. 4. Sample A.1 small reductions (*a*); Sample A.2 large reductions (*b*)

It is likely that during the established rolling process, a sharp change in the friction coefficient between the scale and the roll occurs, resulting in a sudden bending of the strip away from the scale. Adequate modeling of this process was not feasible (attempts to find a suitable friction coefficient or friction law did not yield the desired results), leading to the decision to qualitatively assess the influence of process parameters on bending resistance in the industrial case – i.e., it is necessary to achieve bending like that observed, but in the opposite direction.

To evaluate the possibility of reducing the amount of bending of the rolled product through cooling one side before rolling, a sample with industrial scale was lowered into a water tank to a depth of approximately 1/5 of its thickness with the scale facing down and held for 10–12 seconds before rolling. After cooling in the tank, the surface temperature with the scale was about 100 degrees lower than that of the opposite side. This method allowed the roughing stage to be completed successfully, with significantly lower bending of the rolled product. Curvature changed from 264 mm to 707 mm.

Results of industrial rolling case simulations

Previously, the main methods for controlling the bending of the rolled product during rolling were highlighted. Three cases were modeled: 1) formation of a “linear” (or close to it) temperature gradient across the cross-section of the slab before rolling; 2) selection of the operating mode of the stand descaler during rolling; 3) artificial modification of the friction coefficient on one of the slab surfaces without changing the other process parameters (modeling the diffusive influence of scale).

According to the calculations, the most effective tool for compensating bending turned out to be the method of forming a linear temperature gradient of a certain magnitude across the cross-section of the slab before rolling.

In the developed model for forming the temperature gradient before rolling, the heating of the slab is simulated with different temperature setpoints for the upper and lower zones of the furnace. Subsequently, to obtain the initial temperature field of the workpiece, a holding period is modeled in accordance with the physical experiment, which corresponds to the average time from the slab being removed from the furnace to being fed into the cage. A pause is simulated between passes (time for reversing the rolls and feeding the rolled product into the cage).

The simulation results showed that the rolled product processed with a temperature gradient of 40 °C exhibited bending close to that observed in practice (strong over-bending near the center of the rolled product). **Fig. 5** shows the temperature distribution before the task of rolling in the cage.

The cross-section shape of the rolled product by passes is presented in **Fig. 6**.

In the case of clad rolled products, **Fig. 7** presents an example of changes in the bending magnitude when using a temperature gradient of 40 °C in the billet. Curvature changed from 306 mm to 513 mm. Reducing the bending magnitude leads to a decrease in impact loads on the rollers and plates of the roller table, as well as a reduction in the risk of equipment damage.

Fig. 8 presents the distribution of stresses in the deformation zone during the rolling of the clad sheet. When using a temperature gradient at the interface of the two metals, the average stresses are reduced by 18 %, which decreases the risk of delamination.

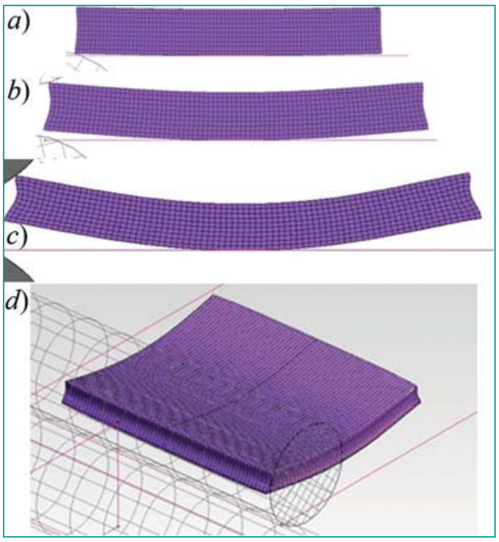

Fig. 6. Shape of the rolled product by passes: 1st pass (*a*), 3rd pass (*b*), 5th pass (*c*), overall view after the 5th pass (*d*)

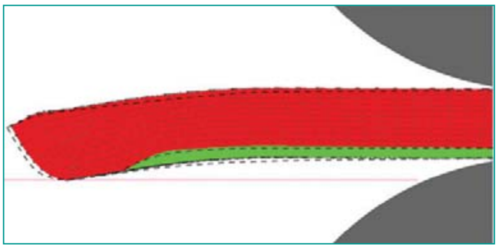

Fig. 7. Comparison of the front-end shape of the clad rolled product (the dashed and the solid lines represent the shape of the roll using and without using a temperature gradient respectively)

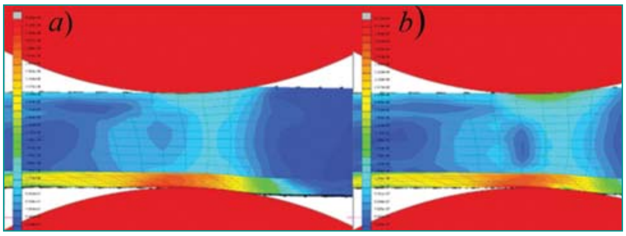

Fig. 8. Comparison of the distribution of equivalent stresses in the deformation zone without using a gradient (*a*) with a temperature gradient (*b*)

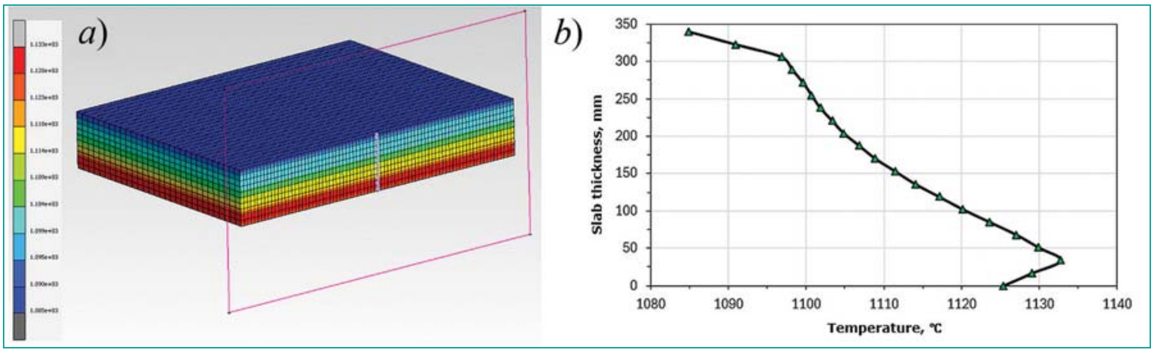

Fig. 5. Temperature distribution of the slab before entering the stand

The heating regime calculation of the slab and industrial testing of the developed solution

The recommendations obtained were applied to calculate the experimental heating regime in the thick plate mill furnace model. Used model is installed at level 2 of mills' furnace automation system. The model parameters were set as the temperatures at the upper and lower surfaces of the slab, as well as the average temperature across the section. The calculation results are presented in **Fig. 9**.

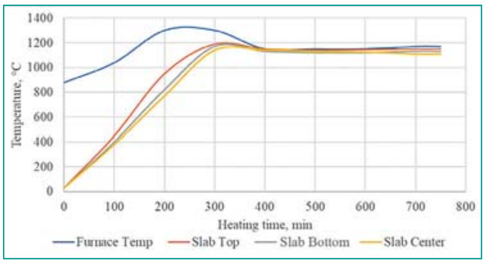

Fig. 9. Simulation of the experimental heating regime in plate mill furnace model

Based on the calculations to create a linear temperature gradient of approximately 40 °C through the slab thickness, the following recommendations are proposed for testing in industrial conditions: set the temperatures in the upper subzone of the holding zone to a target of +30 °C and in the lower subzone to a target of –30 °C, and maintain the holding period for one hour. During the production of the experimental batch of rolled products, it is also necessary to apply existing methods for regulating the amount of plate bending during rolling (rolls speed difference, use of hydraulic systems in the stand).

As part of the industrial experiment, two slabs of steel grade 10KhGSCN2MBF with dimensions of 355×1500×3590 mm, as well as eight packages of the composition 09G2S + + 08Kh18H10T of various sizes for producing clad rolled products, were set for rolling.

As a result of the combined application of the developed heating regime and existing methods for regulating the shape of the rolled product, the required geometric parameters of the 50 mm thick plate from steel grade 10KhGSCN2MBF were achieved. The clad plates also had satisfactory geometry.

Conclusions

1. The conducted studies of the rheological properties of the steel grades presented in the work showed that the flow stress of steel 10KhGSCN2MBF is 24 % higher than that of 09G2S, but 14 % lower than that of 08Kh18N10T. It is also worth noting its greater sensitivity to temperature changes compared to the other two steel grades – by 10 % with an increase in temperature by 50 °C.

2. Laboratory studies demonstrated that local cooling of the slab surface (analogous to the operation of descaling systems installed in the stand) showed limited effectiveness due to the shallow depth of influence. However, its application in combination with other methods has a supplementary effect when correcting the shape of the rolled product.

3. Laboratory experiments confirmed the influence of scale on the formation of strong longitudinal bending of the rolled product due to varied friction conditions on the upper and lower rolls. Accurate modeling of this effect using FEM requires further research.

4. It has been established that forming a linear temperature gradient of 40 °C through the thickness of the slab during heating in the furnace is the most effective way to minimize longitudinal bending of the rolled product. This method also significantly reduces (by 18 %) the average stress at the interface between the cladding and base layers during the rolling of clad slabs.

5. Industrial tests confirmed the feasibility of the proposed method for forming temperature gradients. The combined use of gradient heating, automatic regulation of roll speeds, and descaling systems allowed to produce rolled products with satisfactory geometry without impairing their mechanical properties.

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