Features of finite element modeling for hot rolling process of clad sheets and strips

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This article discusses application of mathematical modeling based on the finite elements method (FEM) to analyze the process of rolling clad sheets and strips. Examples of studies are given, in which FEM was used to analyze the stress state at the interface between layers, to consider the effect of rolls speed mismatch on the rolling process, to determine the criteria for layer adhesion and other process parameters. However, some of these studies do not take into account a number of aspects that can increase modeling reliability. The article considers the most important aspects of development of the model for rolling clad sheets based on the FEM. Two main ways of modeling the clad and base layers are described, setting different properties of the same body or modeling layers by different contact bodies. Particular attention is paid to the choice of model parameters and the correct division of layers into elements to avoid loss of contact and penetration of elements into each other. This article also provides recommendations on the choice of friction coefficients for various contact pairs. When choosing friction coefficients, it is necessary to take into account the materials of the contact surfaces, their condition and operating conditions. In addition, the friction coefficient is an important factor affecting the accuracy of modeling, and it is recommended to compare the simulation results with experimental data to obtain its refined values. Examples of development of the models based on the FEM are given, which were adapted according to the results of laboratory experiments and applied to calculate the parameters of industrial rolling. Satisfactory convergence of modeling results with the results of industrial rolling is shown.

Key words: modeling, finite element method, friction coefficient, clad rolled products, division into elements, relative deformation of layers.

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Introduction

The clad rolling technology is one of the most widely used methods for manufacture of clad sheets and strips. Almost 60 % of large-size clad sheets are manufactured worldwide via this technology, which includes preparation (grinding, cleaning, degreasing) of connecting surfaces of the base and clad layers; their joining via welding; air pumping out of intercontact space through the channels, which were previously prepared in the base layer (pumping-in of inert gas is possible); furnace heating; hot rolling, when joining of the layers (cladding) is occurred [1, 2].

The considered method allows to obtain clad rolled products with high mechanical properties (shear strength is above 300 MPa), however, there are several features in the process of their production, which appear due to difference of the properties of layers (heterogeneity of deformation and temperature, bend of rolled products etc.). This aspect leads to necessity of choosing the optimal thickness of clad layer in composition of initial stacked package for obtaining the required final thickness of clad layer, caused by heterogeneity of deformation of the layers. Development of reduction procedure is also required to provide bonding of layers and equipment safety (due to essential bend).

Choice of the initial thickness of clad layer and other technological parameters can be carried out in experimental mode, however, the cost of one industrial clad slab most often exceeds 10 thousand dollars. Additionally, there are more than 50 combinations of materials and final thickness of the base and clad layers, what makes experimental approach very expensive.

Mathematical models of rolling process, based on the finite element method (FEM) allow to avoid high expenses for conduction of experiments. FEM-based modeling has also other advantages in comparison with carrying out industrial experiments: possibility of varying parameters within wide range of values and to research the processes inside a billet, as well as less time for preparation and conduction of experiments or calculations.

Modeling of the rolling process of clad rolled products was realized only be several researchers. The example of analysis of stress state at the interface between layers in order to extract the criterion of their bonding is presented in the work [3]. It should be noted that Coulomb friction and 2D problem statement were used in this research, while other passed investigations [4-10] testify about necessity of choosing shear friction.

The work [11] considers modeling of the rolling process for rolled titanium-clad products at different thermal and deformation parameters. This modeling was carried out in the ANSYS environment with 3D problem statement. Absence of modeling of an entrance and exit roller table should be noted in this case; it can have influence on the obtained results.

The authors of the research [12] examined the problem of dependence of layers bonding for stainless steel 316L and carbon steel Q345R on technological parameters. A symmetrical "sandwich" was examined in two variants: with stainless steel inside or outside a sandwich. Modeling of the rolling process was conducted using 3D elements and two planes of symmetry (along length or width of metal product). The shear friction model with the coefficient 0.3 was used.

The rolling model for aluminium-clad alloys on the base of the Deform 3D program is considered in the article [13]. The symmetrical task with Coulomb friction coefficient 0.4 is used. 2D problem statement can lead in the case of rolling modeling for clad ingots to inaccuracy in the results (ingot width/thickness relation is less than 5).

The work [14] was carried out to determine the influence of roll speed mismatch and differences of their diameters on the bending degree of clad rolled products made from steel-aluminium composition. 2D model was also used in this research, but entrance and exit roller tables were not subjected to modeling, despite investigation of bending of tolled product.

The authors of the research [15] modeled rolling of a clad billet in order to analyze destruction of materials under deformation along their joining boundary after explosive welding. A phenomenological model for prediction of damages and destruction via lamination under plastic deformation was suggested on the base of stress state analysis in the intermediate layer.

The existing researches testify mainly about the results of modeling, but not about the process of model creation and influence of its parameters on the obtained results. This paper is devoted to description of the aspects of FEM models creation for rolling of clad sheets.

The aim of this article is consideration of the main aspects and features of modeling of the rolling process of clad rolled products on the base of conducted investigations and practical experience of the authors.

Materials of the research

The article considers the problems of modeling of rolling and cooling of clad rolled products of the following steel grades: pipe steel of K60 strength class (further K60 steel)+AISI 316L, 09G2S+VT1-0, 10G2FBYu+AISI 316L, K60+08Kh13, 22K+08Kh18N10T, 12KhM+ 10Kh18N10T, 09G2S+08Kh13. The observed combinations of composition cover the most part of consumed grade range of clad steels in oil and chemical, nuclear engineering and tube manufacturing industries in Russia. Two variants of constructions of bimetallic sandwiches are observed: non-symmetric open and closed sandwiches, their examples are shown on the **Fig. 1**.

Most often a clad slab consists of two or more layers, which are joined via welding along the billet perimeter; however, there is no bonding of layers in the other billet part. When choosing the common model parameters on the base of FEM, separation of the layers to elements and modeling methods for different layers (by two contact bodies or by one body with various material properties) are the main problems to be solved.

Methods for determination of the layers of clad rolled products in FEM models

When meshing the layers to elements, it is recommended to choose the same size of elements based on the dominant direction. This approach allows to avoid contact loss and mutual penetration of elements inside each other in the case of “node-to-segment” contact type (**Fig. 2**).

If this approach is not applicable (e.g. in the case of modeling of incomplete bonding in the first passes), it is recommended to use “segment-to-segment” contact type, what can decrease possibility of contact loss.

It is suggested to simulate a clad layer with welded leg (**Fig. 3**), what accelerates calculation of biting process in the first pass and makes the model closer to reality. Right angles in the points of contact between clad layer and rolls or top of rolled products should be avoided, because it leads often to the contact between corner of an element and a segment of another element, what finalizes in its turn in mutual penetration (see Fig. 2).

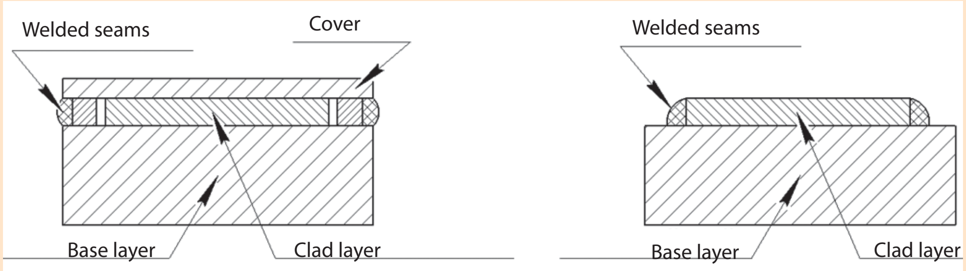

Fig. 1. Constructions of sandwiches, which are considered in this article

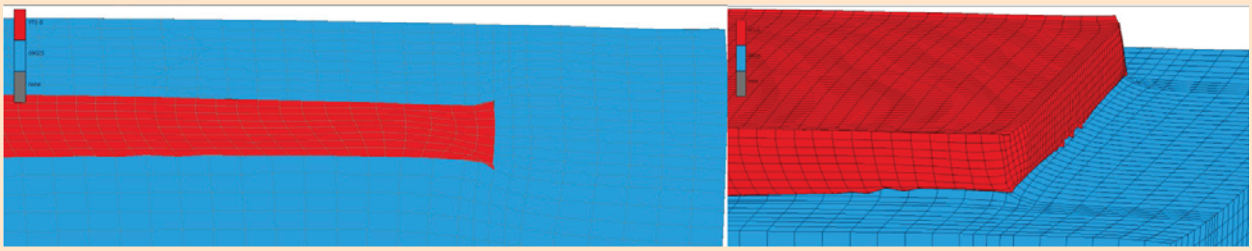

Fig. 2. Examples of modeling results with mutual penetration of elements inside each other

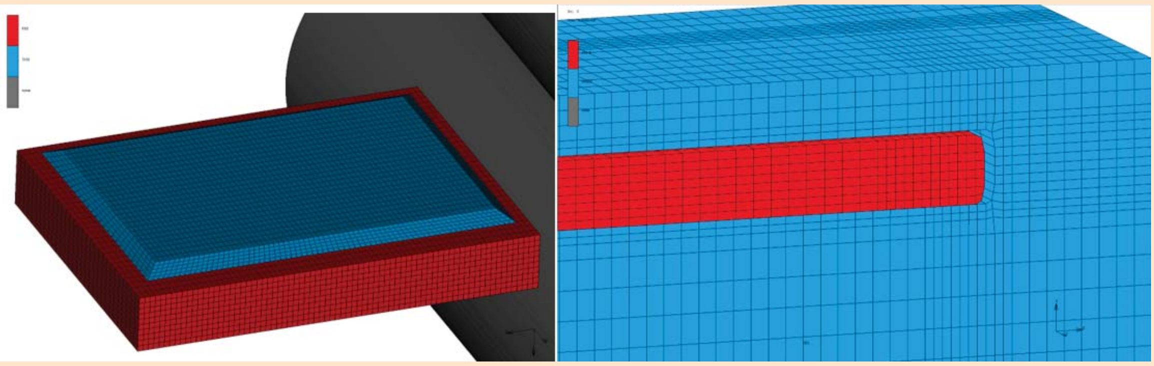

Fig. 3. Examples of modeling of clad layer with welded leg and rounding-off of corners for the case of closed sandwich

There are two main methods for presetting clad and base layers of rolled products. The first includes presetting different properties of the same body, the second is based on modeling of layers by different contact bodies. Let us consider both approaches on the example of the 10G2FBYu+316L composition with thickness 14+6 mm, which is subjected to one pass rolling with reduction 14 %. Equivalent stresses for both cases are displayed on the **Fig. 4**. It can be seen that the difference is in presence of the boundary in stresses distribution. If two different bodies are preset, stresses are distributed with distinct boundary between them; probably, it corresponds to the real picture in maximal form, taking into account different stress of materials flow for similar or identical deformation along the axis Ox (for the case of bonded layers). If one body with different properties is preset, stresses are distributed homogeneously. The maximal values of stresses are practically identical, the same observation can be related to forces and torques, which are characterized by difference by 2-5 %. Nevertheless, the differences in the shape of edges and in the radius of strip bending are seen. Comparison of distribution of equivalent plastic deformations, where the difference on the separation boundary of two layers is seen, is shown on the **Fig. 5**. The base layer is characterized by larger deformation for the case of contact between two bodies, while in another case deformations are continuously distributed; as a result, the elements, which are located near the boundary of the base layer, are subjected to smaller deformation. Comparison of modeling results and practical experience displays that the second method is more preferable and provides more exact results.

Choise of friction coefficients for different contact pairs

Friction coefficient is preset according to the three main laws (Coulomb, Siebel and mixed) during simulation. When using the Siebel law, the friction coefficient during rolling is situated within the range 0.4-0.6; larger value is valid for a biting process, smaller – for a steady-state process. When using the Coulomb law, the friction coefficient during rolling is situated within the range 0.2-0.4 [16, 17]. It is recommended to use the Siebel law [4-10]. Shear friction is based on the theory of plastic deformation of materials and takes into account such factors as contact pressure, strain rate and relative motion of a tool surface. Shifting friction allows to predict more precisely forces, energy and temperature, which appear during hot rolling process. In this case, Coulomb friction does not take into account plastic deformation of material and interaction between the layers (which are subjected to plastic deformation) and tool surface. It is based on ideal slipping between the surfaces without physical variations occurring during this process. Thus, Coulomb friction does not allow to take into account all forces and factors, which gave the effect on hot rolling process.

The friction coefficient is higher for stainless steels of austenite class than for low-carbon low alloy steels [18, 19]. The authors carried out the work using laboratorial rolling of samples from stainless steel 316L, with clad layer. Shear friction with friction coefficient 0.4 for the base layer and 0.6 for the clad layer was selected for preliminary modeling. Comparison of the modeling results with experimental

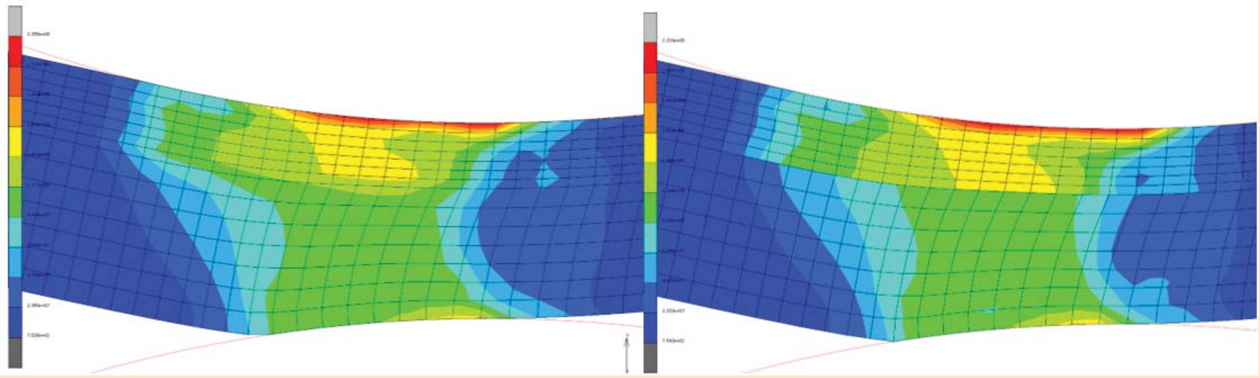

Fig. 4. Comparison of distribution of equivalent stresses during modeling of layers by one body (left) and two bodies (right)

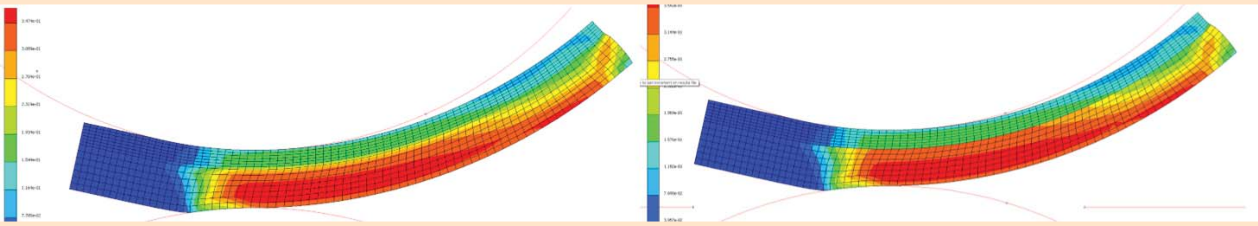

Fig. 5. Comparison of distribution of equivalent deformations during modeling of layers by one body (left) and two bodies (right)

results on the base of laboratorial mill displayed the error 7-10 % for rolling force and 25-30 % for strip bending values. After varying the friction coefficient for stainless steel to 0.5, the error decreases to 5-7 % for rolling force and 5-10 % for strip bending values.

Due to incomplete bonding of the layers after first and second passes, it is required to take into account friction between the clad and base layers. In this case, it is suggested to use the friction coefficient which is identical to friction between a roll and rolled product from stainless steel. Use of such approach displayed good results during modeling of rolling process for steel-titanium composition in a closed sandwich construction; titanium distribution inside a cavity of closed sandwich shows good correlation with the results of laboratorial rolling.

Influence of material properties on modeling

Due to different properties of the clad and base layers, the rolling process conducts in non-symmetric mode, and use of symmetry is possible only along width (in the case of 3D modeling). When the values of deformation resistance of the clad layer are higher in comparison with the base layer, rolled products is bending to its side; at the same time, industrial rolling is carried out with more hard layer below, what causes necessity in simulation of operation of roller tables. Modeling of roller tables can be realized in the form of geometrical bodies (planes / lines) with presetting of low friction coefficient because rollers of a roller table are rotating with rolling speed.

Accuracy of a FEM-based model is determined by preset properties of materials (both mechanical and thermal-physical). Most exact results can be obtained on the base of testing for compression or twisting [20]. Testing for compression in the Gleeble-type units is most widely distributed. Difference in material resistance can reach 30-50 %, and this relationship is varied within different temperature range, what provides additional necessity of experimental data on deformation resistance of layers.

Difference of thermal-physical properties (heat capacity, heat conductivity, density etc.) of layers and, in particular, thermal expansion coefficient, leads to different cooling speed of the layers and appearance of the temperature gradient, what in its turn finalizes in bending of a rolled product. For example, heat conductivity of the steel Kh18N10T is lower than heat conductivity of the steel 09G2S by 30 % [21], what leads to the temperature gradient 30-40 °C in the case of homogeneous cooling of clad rolled products. The example of the temperature gradient during cooling of the clad rolled product with thickness 110 mm (5+105 mm) from 900 °C to 500 °C (it is shown in Fig. 6). Presence of the temperature gradient and difference of the thermal expansion coefficient lead to bending of the clad rolled product during its fabrication, what should be taken into account during modeling of both rolling and cooling processes.

Existence of phase transformations, which vary cardinally thermal-physical properties of the rolled product and its volume, should be also taken into account. In this case, transformations occur in different temperature ranges of stainless and carbon steels, what stipulate additional effect on forming in a rolled product during cooling.

Practical examples of FEM-based modeling use

The authors carried out the work on research of relationship between the coefficient of relative (dependent) deformation and technological parameters of the process for consequent combinations of clad strips: 10G2FBYu+316L; K60+08Kh18N10T; 12KhM+10Kh18N10T. This coefficient shows degree of increase or decrease of clad layer deformation relating to the base layer. The experiments were conducted in laboratorial conditions.

The developed FEM-based model was adapted according to the results of laboratorial rolling experiments, accuracy of rolling force predictions were about 8 %, good convergence of bending radii and edge form of strips was obtained for different rolling conditions (**Fig. 7**).

Use of the FEM-based model allowed to expand essentially the research area owing to conduction of numerical experiments within the wide range of reduction, temperature and thickness values of clad layers. Additionally, the features of distribution of stresses and deformations along thickness of rolled products were examined. The obtained results made it possible to calculate parameters of industrial sandwiches, reduction procedures, and to obtain the required thickness of the clad layer, as well as high-quality bonding of layers.

The authors carried out the work on examination of regularities of the process of steel and titanium joint deformation during laboratorial rolling of the clad slab (closed non-symmetric sandwich, see Fig. 1). In the same way as in the previous case, the FEM-based model was used for analysis of relative deformation of layers and features of titanium forming in a closed sandwich.

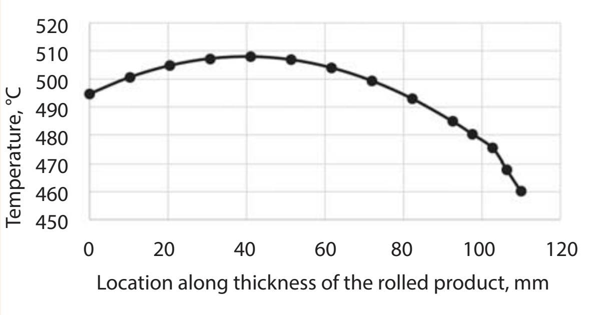

Fig. 6. Example of the temperature gradient during cooling of the bimetallic rolled product with thickness 110 mm from 900 °C to 500 °C

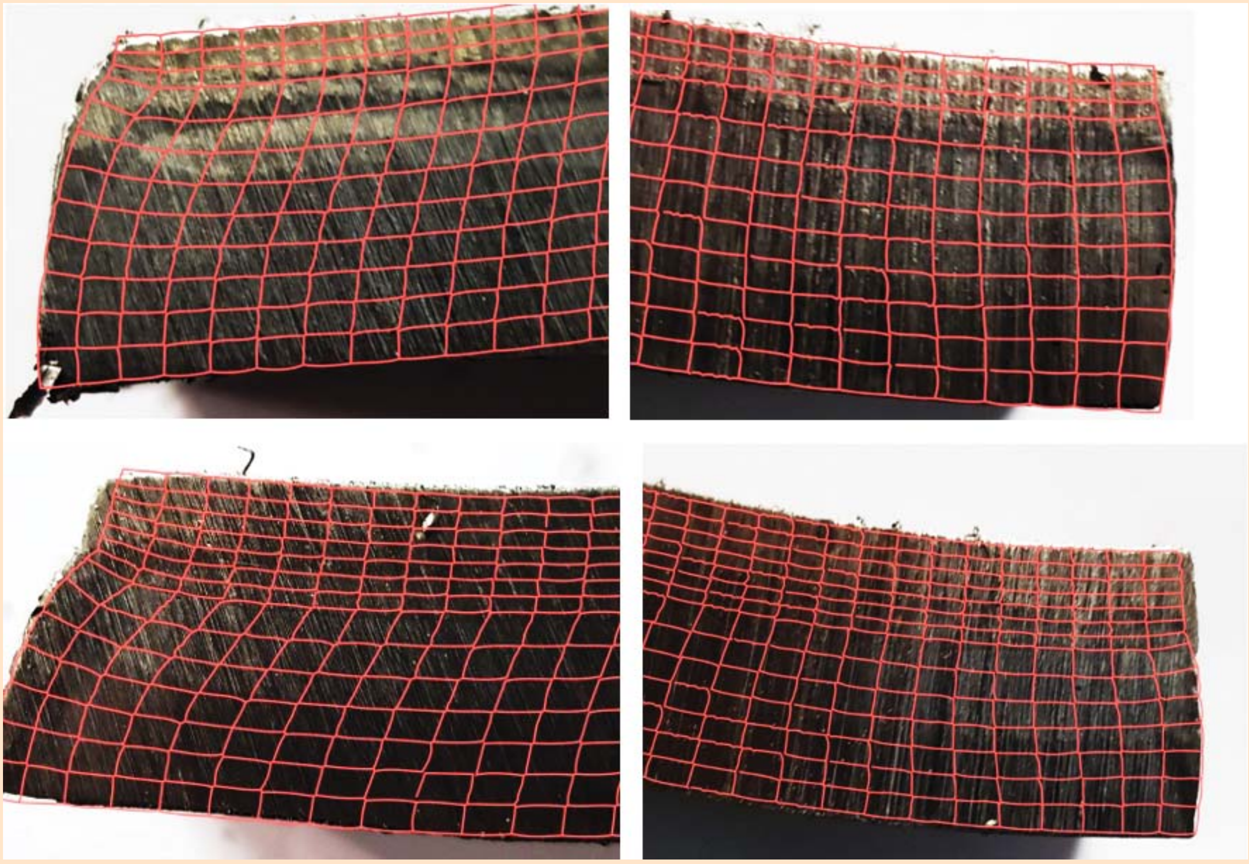

Fig. 7. Comparison of the form of front and rear strip ends, obtained during laboratorial rolling, with the modeling results

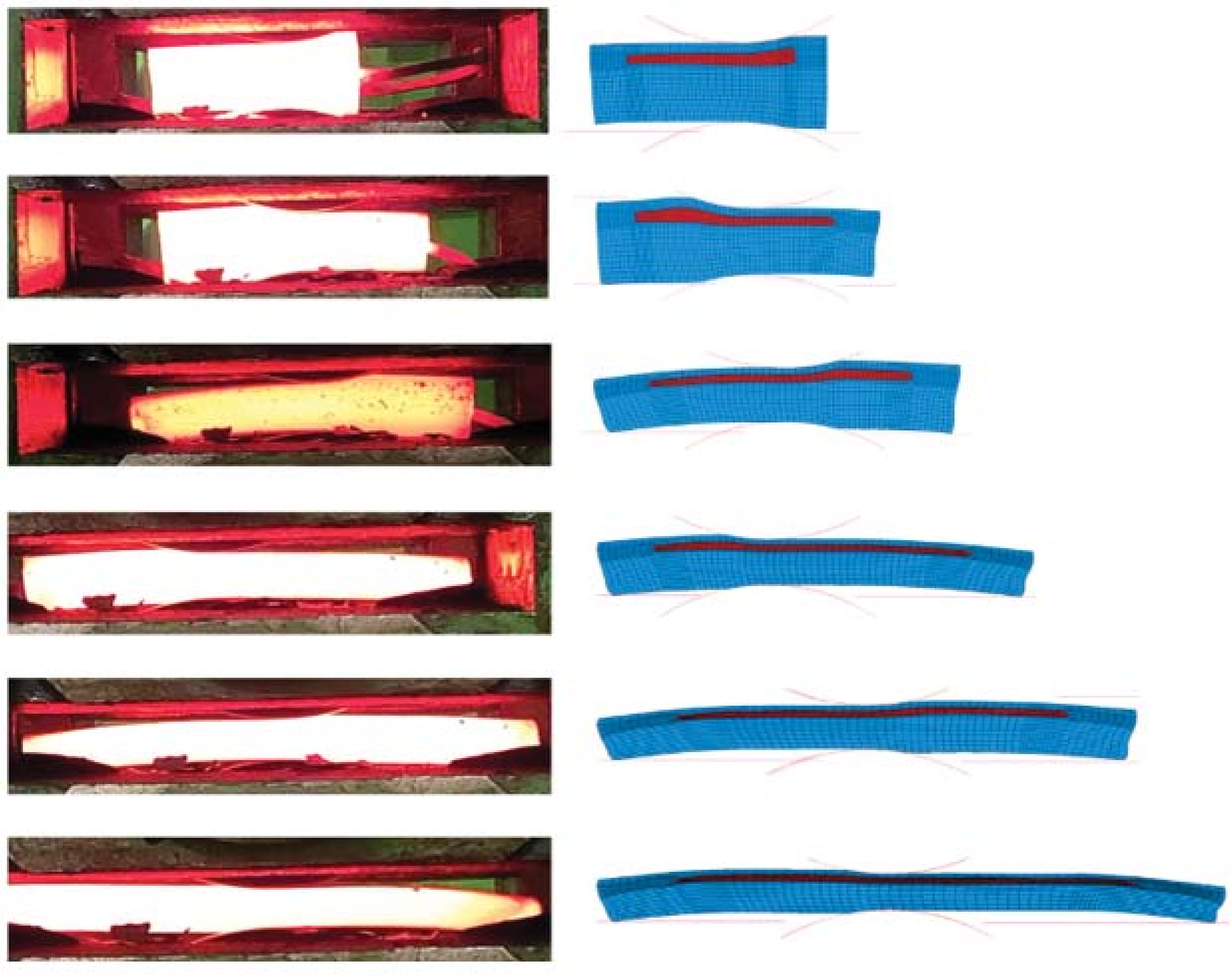

Fig. 8. Comparison of billet form (closed sandwich) during modeling and laboratorial rolling

The developed model displayed satisfactory results on thickness and form of a clad layer after adaptation, in comparison with laboratorial samples after rolling. Difference in clad layer thickness didn't exceed 5-10 %. Bending of rolled product is compared during modeling and actual rolling of a package (**Fig. 8**).

Comparison of form and thickness of the clad layer after rolling between the results of modeling and laboratorial processing is presented on the **Fig. 9**.

Modeling displayed that thickness deviation of the titanium alloy made up to 12.5 % in longitudinal direction and up to 4 % in transversal direction. This fact was taken into account during development of industrial sandwich construction (selection of side and transversal plates, choice of initial thickness of rolled product).

Modeling of rolling process allows to analyze not only laboratorial cases, but also industrial ones. A model, which is adapted during laboratorial experiments, can be successfully scaled for rolling in heavy plate mills. The authors have analyzed joint deformation for different combinations of materials [22]. Determination of relative deformation of a clad layer was the aim of this work; for this purpose, its thickness after rolling was examined on the base of modeling and the results of manufacture of industrial clad sheets. The results of modeling and measurements are presented in the **Table**, they manifest satisfactory convergence.

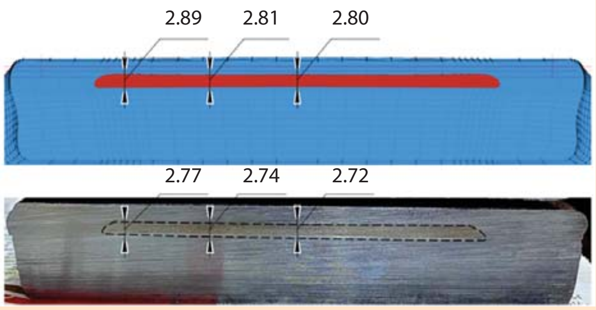

Fig. 9. Comparison of form of the clad layer in the cross section of a sandwich

In addition to final thickness of a clad rolled plates and sheets, its form was also analyzed. Increase of

Comparison of final thickness of clad layer in the cases of modeling and industrial rolling

Composition	Initial thickness of clad layer, mm	Final calculated thickness of clad layer, mm	Measured thickness of clad layer, mm
K60+316L	35	3.44 (center)	3.5-3.7 (center – front sheet edge)
09G2S+08Kh13	40	5.15 (center)	5,1-5,3 (center – front sheet edge)

its thickness was observed, both in direction to side planes and in directions to front and rear billet ends for more consistent materials. Thickness of a clad layer in the center of rolled metal is practically constant. For more "soft" stainless steel 08Kh13, clad layer is practically uniform. Thickness deviation in sub-side and central areas makes up to 15 % for the steel 316L.

Conclusions

1. Modeling of rolling process for a clad billet is a complicated task and has several features, which are considered in this article. It is necessary to take into account non-symmetric character of the process, various mechanical and thermal-physical properties of layers, as well as different friction coefficient for the clad and base layers.

2. The developed FEM-based models allows to provide a choice of optimal initial thickness of a clad layer and to choose reduction and cooling parameters, taking into account the forming features of clad sheets during rolling.

3. The examples of practical use of the developed models for solving practical technological problems are presented in this article; satisfactory accuracy of the developed solutions is displayed.

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