Study of joint hot deformation of nickel alloy and low carbon microalloyed steel in manufacture of heavy plate clad rolled products

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Clad pipes are widely used worldwide for transportation of oil and gas under conditions of exposure to aggressive media. The article investigates the issue of joint deformation of nickel alloy and steel of strength class K60 during production of rolled heavy plates on the industrial plate mill. The rheological properties of the constituent materials were determined, the mathematical model based on the finite element method was developed; it allowed to determine the dependence of deformation ratio of the layers on the total deformation of the billet. Accuracy of the results obtained using simulation is confirmed by comparison with the results of industrial rolling. The obtained relationships allow proper selection of the initial thickness of the stainless layer billet, which provides the required final thickness of the clad layer.
Keywords: nickel alloys, clad pipes, clad rolled steel, Gleeble, DUO-300 rolling mill, laboratory rolling, finite element method, modeling, joint deformation, layer deformation ratio.
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Introduction

Oil and gas production remains at a fairly high level [1] and new types of pipe products are required for their transportation [2].

High CO_2 content in the transported medium leads to corrosion and, consequently, to quick decrease of a pipe weight; it should be noted that this decrease accelerates at the high temperature. Presence of H_2S causes sulfide corrosion cracking under stress at high temperatures. Steels and alloys with high chromium and/or nickel content are usually characterized by good corrosion resistance to stress-corrosion cracking (SCC) in the solutions containing Cl at high temperatures; it stipulates their use as material for transporting pipes. Such steels as 08Kh18N10T (AISI321), 10Kh17N13M2 (AISI316L), as well as nickel alloys [3] can be mentioned among the materials which are resistant to different kinds of corrosion and used in the pipeline transport.

In addition to providing high corrosion resistance, it is necessary to keep high productivity of pipelines, so it is required to use high pressures. High-strength low-alloy steels (such as K60) can be used to solve this problem owing to their high mechanical properties [4, 5], while they are rather more cheap than nickel alloys.

The clad pipes which combine the properties of both these products (low-alloy steels corrosion-resistant alloys) are practically used; they allow to obtain high mechanical properties together with required corrosion resistance and less metal intensity.

Manufacture of clad sheets and pipes is weakly developed in Russia. At the same time, these products are required in the future [6].

The manufacturing methods for such pipes can be different:

- facing of the pipe internal surface;
- hydroforming technology, pipe-in-pipe;
- pipe manufacture from clad rolled products via forming.

This method was also studied in this paper.

Selection of clad layer thickness is one of the main questions during clad rolling from the point of view of manufacturing technology. Different materials are subjected to deformation in different ways, taking into account possibility of variations not only in the clad layer, but also in the main layer. It is possible to choose the required initial thickness of the clad layer to provide the preset final thickness based on information about relationship between deformation of the clad layer and deformation of the main layer. It should be mentioned that loss of even one sheet due to non-conformance of the final thickness of the clad layer to standard requirements can finalize in additional expenses up to RUR 2-5 mln., depending on clad layer material.

Determination of the deformation relationship between the main and the clad layers from steel of strength class K60 and Ni Alloy nickel alloy was the aim of this work. It was emphasized on the clad layer from the nickel alloy, because it is the less examined regarding joint deformation with low-alloy steels; however, other compositions were also studied and the results are presented for comparison and confirmation. To achieve the formulated aim, the following tasks were solving:

- determination of rheological properties of steels for the main and the clad layers within the wide range of deformation, deformation rate and temperature values at the Gleeble unit;
- creation of the finite element model of rolling process for clad samples;
- laboratorial rolling of samples at various deformation parameters;
- model adaptation and comparison of the simulation results with the results of laboratorial tests;
- simulation of industrial cases of clad sheets rolling and comparison with the practical results;
- determination of the deformation relationship between the main and the clad layers for the composition K60 + nickel alloy on the base of simulation.

Materials and methods

Relationships between deformation resistance and deformation parameters for K60, 09G2S, 08Kh13, 316L steels and Ni Alloy were examined in this work. Chemical composition of these steels is presented in the **Table 1**.

The tests were conducted at the Gleeble 3800 unit using cylinder samples with diameter 10 mm and height 15 mm, for three deformation speeds (0.1; 1.0 and 10 s^{-1}) and within the temperature range 850-1200 °C. To provide reliability of testing, the thermal cycle according to the following parameters was used.

1. Treatment for solid solution:
- heating speed: 0,35 °C/s;
- heating temperature: 1250 °C;
- holding at heating temperature: 30 min;
- speed of cooling down to the room temperature: more than 200 °C/s.

2. Deformation test:
- heating speed: 5 °C/s;
- heating temperature: 1150 °C;
- holding at the temperature 1150 °C: 120 s;
- value of preliminary deformation: 0.1;
- rate of preliminary deformation: 1 s^{-1};
- holding after preliminary deformation: 20 s;
- speed of cooling down to the testing temperature: 10 °C/s;
- holding at the testing temperature before main deformation: 10 s.

Laboratorial rolling was conducted at the DUO-300 rolling mill 300x250 in the conditions of TSNIIchermet named after I.P. Bardin. The main characteristics of the mill stand are as follows: roll diameter 300 mm; roll barrel length 250 mm; maximal rolling force 1.7 MN (170 t); maximal rolling torque 0.061 MN·m; electric power of the main drive 110 kWt; rolling speed 50-300 mm/s.

The mathematical model, which is described in this paper, is based on use of the finite element method (FEM) for 2D case using 4-node elements and for 3D case using 8-node elements. Symmetry is not used due to variety of properties of the main and clad layers. Simulation was conducted in the ANSYS medium.

Study of materials properties at the Gleeble unit

Examples of the results obtained at the Gleeble unit for all examined steel grades (testing temperature 1100 °C, deformation rate 1 s^{-1}) are presented on the **Fig. 1**.

Fig. 1 testifies that Ni Alloy and 316L are the most strong materials, while the steel grades 09G2S, K60 and 08Kh13 have approximately equal properties. The curve “stress – deformation” for the Ni Alloy (**Fig. 2**) has a section with linear elevation of stresses at the temperatures less than 1000 °C, what means domination of strengthening processes comparing with softening processes. This feature will be described with more details further during analysis of laboratorial rolling of samples.

Conduction of laboratorial experiments

After assembling of laboratorial samples, their vacuum treatment was conducted to the value 3x10-2 mm of mercury; for this purpose a hole with diameter 4 mm and depth 40 mm is drilling from the edge of the main sandwich layer. Then another hole with diameter 4 mm is drilling in the plane of contact between the layers in such way that it connects with the horizontal hole at the distance 35 mm from the edge.

Initial and final dimensions of billets and rolled strips are presented in the **Table 2**, while the measuring scheme and the view at rolled strips are displayed in the **Fig. 3** and **Fig. 4** respectively. It should be noted that billets of the main and the clad layers were subjected to milling before

Table 1. **Chemical composition of the samples which were examined at the Gleeble unit**

Steel grade	Mass part of the elements, %							
	C	Si	Mn	Cr	Mo	Ni	Nb	Ti	V
316L	0.02	0.54	1.37	18.6	2.69	11,97	-	-	-
K60	0.06	0.26	1.82	0.17	-	0,27	0.034	0.016	0.031
Ni Alloy	-	-	-	22.0	9.0	61.0	4.0	0.2	-
09G2S	0.11	0.55	1.63	0.03	-	0.01	-	0.005	-
08Kh13	0.08	0.32	0.51	12.4	0.026	0.12	0.012	0.003	0.043

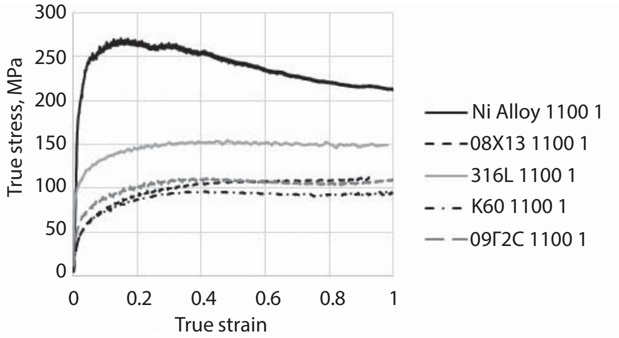

Fig. 1. Examples of the curves obtained during testing at the Gleeble unit

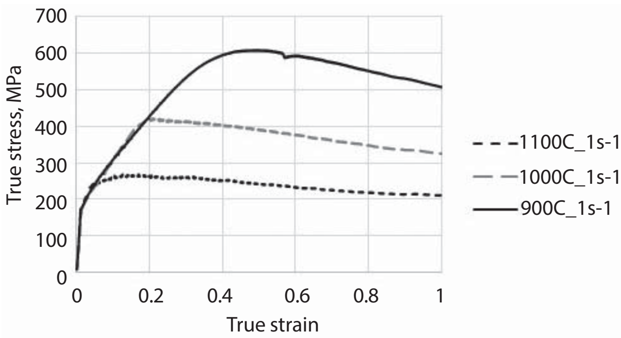

Fig. 2. Influence of the temperature on the properties of Ni Alloy during testing at the Gleeble unit

Table 2. **Geometrical dimensions of initial sandwiches and finished strips**

№	H	H_{bas}	H_{clad}	h	h_{bas}	h_{clad}	B_{bas}	B_{def}	B_{clad}	b_{bas}	b_{def}	b_{clad}	L_{bas}	L_{def}	L_{clad}	l_{bas}	l_{def}	l_{clad}
1	73.7	58.8	14.9	15.5	10.3	5.2	100	100	70	130	104	76	200	200	170	730	500	450
2	73.3	58.7	14.6	12.5	8.6	3.9	100	100	70	125	104	75	200	200	170	930	700	600
3	73.5	58.7	14.8	18.1	12.5	5.6	100	100	70	131	104	74	200	200	170	635	510	430
4	73.5	58.7	14.8	18.1	12.5	5.6	100	100	70	131	104	74	200	200	170	630	510	430
5	73.5	58.7	14.8	23.6	16.5	7.1	100	100	70	131	104	74	200	200	170	485	405	330
6	73.5	58.7	14.9	12.6	8.3	4.3	100	100	70	141	100	73	200	200	170	850	660	580

assembling, thereby they have minimal thickness deviation. Measurements in 9 points of the main and the clad layers displayed thickness variation within the range +/- 0,1 mm. This error was considered as accessible one, so thickness values of initial billets were averaged through all measurements.

The following measuring rules were applied:

1. Measurement of clad layer thickness is conducted in the middle of rolled strip length;

2. Length and thickness of a clad layer is measuring both for deformed seam (b_{def}, l_{def}), and without it (b_{clad}, l_{clad}).

The procedures of rolling in the laboratorial mill are presented in the **Table 3**.

Description of the finite element model

2D and 3D goal setting for final element modeling were used in this research. 2D modeling was conducted for the sample No. 2. The model includes six bodies: pusher, billet, two tables, upper and lower rolls. All bodies except a billet are solid, without division to the elements [7, 8]. Billet modeling was realized via division to 4,000 elements of clad layer with welding seams, the main layer was divided by 15,000 elements. Welding seam was separated to triangular and quadrangular elements, the rest part of billet – only to quadrangular elements. The boundary conditions were added to take gravitation into account.

Heat transfer coefficients from strip to roll and from strip to table are presented in the **Table 4**.

As soon as a strip lays on the table metal surface with its lower surface, heat transfer here differs from heat transfer on the upper plane in such way that it can influence of correctness of determination of strip end bending (forming of so-called "ski").

To obtain initial temperature strip field, holding during 10 s was simulated; it corresponds to average time of billet transportation from the furnace to the rolling stand. To obtain initial billet temperature before finishing passes, holding in accordance to the experiment was simulated.

Thermal properties of materials were preset according to the data [9].

Connection of stresses and deformations of strip material was preset using elastic-plastic model of material behaviour. Plastic properties were preset on the base of the data obtained at the Gleeble unit. Elastic properties were preset in correspondence with the data from open sources [10].

Analysis of obtained results of 2D model simulation for laboratorial rolling

The following main features of rolling process can be emphasized due to essential difference between the properties of the main and clad layers [11]:

- strip is bending to the side of the clad layer;
- "leakage" of the main layer over the clad layer was observed just after the second pass at the head and rear parts of rolled product (this result coincides with observations during laboratorial rolling tests).

The value of strip bend after the second pass did not allow to conduct consequent rolling, thereby the billet was overturned and rolled with the clad layer down.

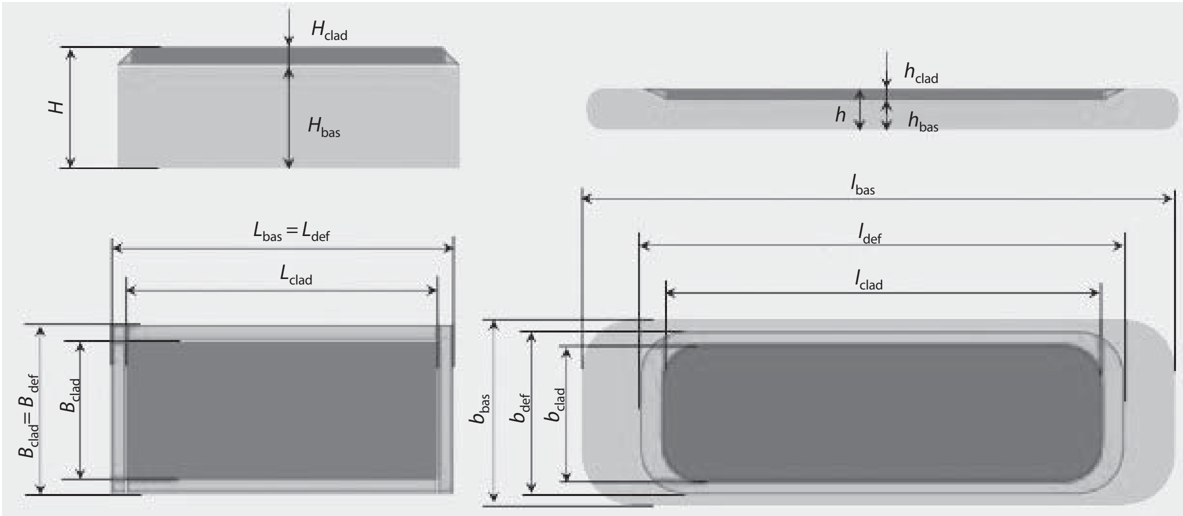

Fig. 3. The main dimensions of a sandwich (left) and a strip (right)

Fig. 4. The view of rolled laboratorial strips

Analysis of the nickel alloy deformation curves led to the conclusion about significant strengthening, which should be taken into account during simulation. Comparison of the forces, with and without accounting of deformation accumulation, is displayed on the **Fig. 5**. It was established empirically that residual deformation makes about 30 % of previous deformation, and deformation accumulation starts at the temperature 880 °C and higher.

Based on the analysis of strip bending degree (**Fig. 6**) in laboratorial rolling tests and simulation, it was decided to use the same friction coefficient (0.6) between the rolls and both strip layers. Friction in the model was preset according to Siebel [12, 13].

Analysis of simulation for 2D case displayed unsatisfactory results in accuracy of the clad layer thickness determination for all modeling cases. E.g., the final value of clad layer thickness was 3.64 mm, while the measured value constituted 4.00 mm.

Absence of flat deformation owing to essential difference of the properties of the main and clad layers, as well as small width of rolled billet in the laboratorial case can be considered as the main cause of non-conformity of the clad layer thickness in 2D simulation. It can be observed in the cross section of rolled strip, where non-uniformity of the clad layer thickness can be seen practically along whole width of rolled material (**Fig. 7**).

3D model was used consequently, all its parameters are the same as for the 2D model. General view of this model is showed on the **Fig. 8**.

The results of simulation using 3D model displayed good repeatability with the results of laboratorial rolling tests. The final strip dimensions – width of the clad layer and whole billet, thickness of the clad layer in different cross sections – are close to real ones (see **Table 5**).

The forces were compared via cutting off the moments of roll biting of a strip and its exit from the roll gap, then the average value was taken for remaining section. The obtained results on forces displayed that simulation with accounting of 30 % strengthening after reaching the temperature 880- 900 °C by the clad layer provides rather precise results. The average error makes 4.3 %, the maximal one – 7 %.

Shape of the clad layer after all passes, which was obtained during simulation, is characterized by thickening at the distance about 20 mm from the front and rear end parts of the clad layer. This shape in its cross section displays good correlation with the shape obtained during laboratorial rolling tests.

Based on these results, it can be concluded about satisfactory accuracy of simulation using the obtained model.

To solve the main task – determination of relationship between deformation of the main and clad layers – we introduce the concept of relative deformation. It means relation between the values of relative thickness of the clad layer in the beginning and in the end of deformation:

Table 3. **Procedures of rolling in the laboratorial mill**

Stage	No. of pass	1			2,6			3,4		
		t,°C	h, mm	ε, %	t,°C	h, mm	ε, %	τ,°C	h, mm	ε, %
Roughing	1	1200	56.7	23	1200	57.0	22	1200	57.0	22
	2		43.9	23		43.9	23		43.9	23
Finishing	3	956	34.0	23	942	37.3	15	931	34.0	23
	4		26.0	23		31.7	15		27.7	19
	5		20.0	23		27.0	15		23.4	16
	6	908	15.6	23		22.9	15		20.3	13
	7					19.5	15	855	17.9	12
	8					16.5	15			
	9					14.0	15			
	10				795	12.0	14			

Stage	No. of pass	5		
		t,°C	h, mm	ε, %
Roughing	1	1200	57.0	23
	2		43.9	23
Finishing	3	928	34.0	23
	4		27.7	19
	5	882	23.4	16
	6			
	7			
	8			
	9			
	10			

Table 4. **Heat transfer coefficients from strip to roll and from strip to table**

Temperature, °C	Heat transfer coefficient, Wt/m² K	
	Strip-roll	Strip-table
800	8000	80
900	9000	100
1000	10000	120
1200	11000	150

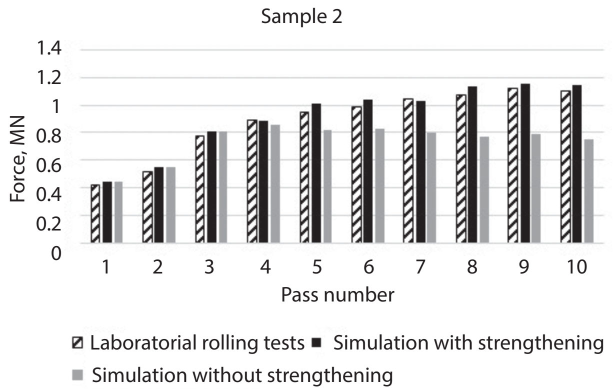

Fig. 5. Comparison of the force calculation with and without strengthening

$$\vartheta = \frac{H_{\text{total init}}}{h_{\text{clad. init}}} \div \frac{H_{\text{total final}}}{h_{\text{clad. final}}}$$

This value is varying depending on general logarithmic deformation for rolled laboratorial samples in the following way (see **Fig. 9**). This relationship between relative deformation of the clad layer and general logarithmic deformation is described well by a degree function. This relationship for the samples 1-5 is close and can be expressed by the following formula:

$$\vartheta = 1.49 \cdot \varepsilon_{\ln total}^{0.157}$$

As for the sample 6, smaller deformation of the clad layer is observed (the coefficient ϑ is larger). The relationship is as follows:

$$\vartheta = 1.56 \cdot \varepsilon_{\ln total}^{0.195}$$

The maximal coefficient of relative deformation is equal to 1.75 for the sample 6, for general logarithmic deformation 1.76. As for the samples 1-5, this coefficient is equal to 1.65, for the same total deformation. As it was already mentioned before, the deformation coefficient at laboratorial rolling tests is higher in comparison with the case of rolling of commercial slabs, due to absence of flat deformation in strip center.

Simulation of rolling process in industrial conditions

3D model was also chosen for analysis of deformations relation during rolling in industrial conditions. Parameters of this model were varied only for geometrical dimensions of rolls and billet, as well as separation of the clad and the main layers to components.

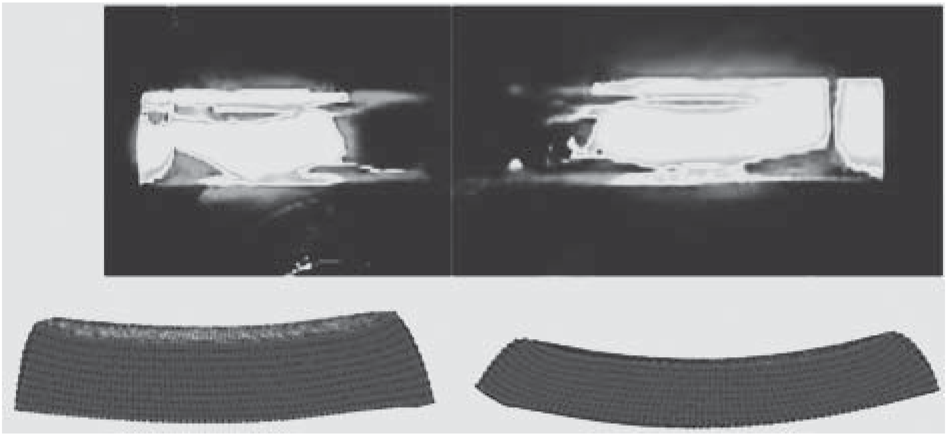

Fig. 6. Comparison of calculated and experimental billet curvature after the 1st and 2nd passes

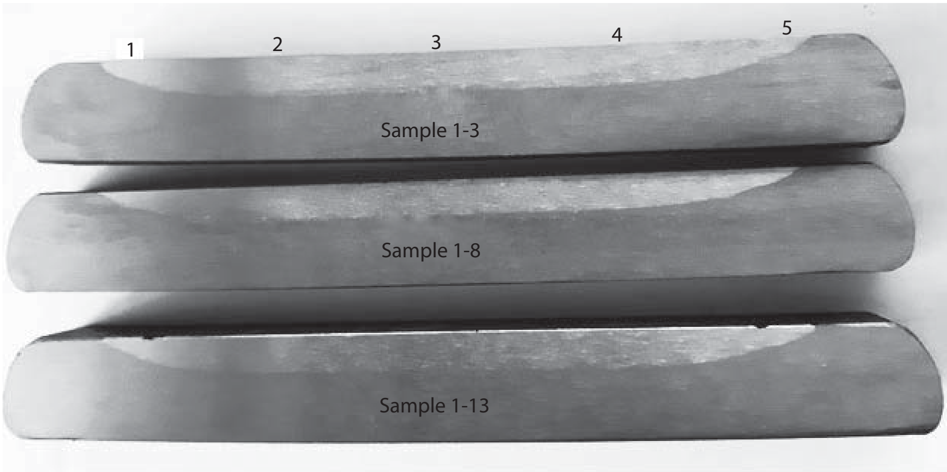

Fig. 7. Picture of a strip cross section

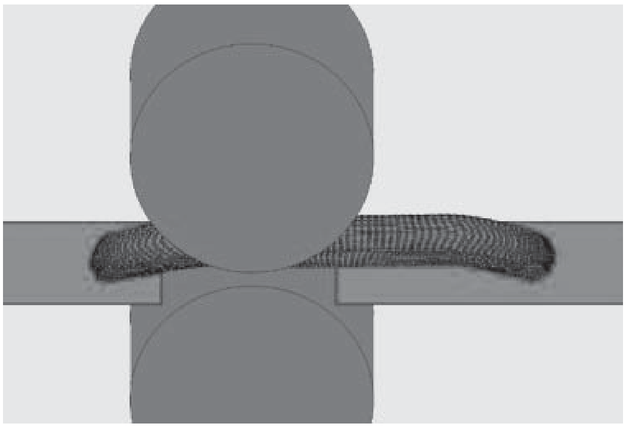

Fig. 8. General view of the 3D model

Table 5. **Comparison of the calculated and measured clad layer for laboratorial samples**

Number of sample	Final calculated thickness of the clad layer, mm	Measured thickness of the clad layer, mm
1	4.84	4.90
2	4.10	4.00
3	7.05	7.10
4	5.58	5.60
5	4.36	4.30

To confirm correctness of the results obtained in industrial conditions using the model, the rolling procedures were simulated at the industrial plate mill; they are presented in the **Tables 6** and **7**.

The schedule No. 1was used for rolling of clad strip made of the composition with steel of strength class K60 and stainless steel 316L. The schedule No. 2 was used for manufacture of clad rolled composition 09G2S+08Kh13. It should be noted that the schedule No. 1 was simulated for the main researched composition K60+Ni Alloy.

The main difference for simulation of rolling in industrial conditions concludes in deformation and, respectively, in shape of the clad layer: increase of its thickness both

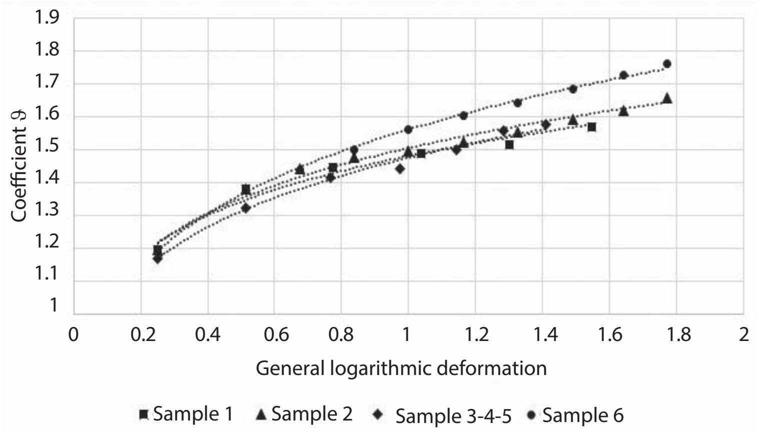

Fig. 9. Relationship between relative deformation of the clad layer and general logarithmic deformation

Table 6. **Reduction schedule No. 1**

Composition: K60+316L				
No. of pass	Thickness, mm	Reduction, %	Width, mm	Length, mm
0	257		2500	2900
1	216	16 %	2531	2944
2	197.26	9 %	2576	2980
3	179.75	9 %	2981	2653
4	161.8	10 %	2983	2946
5	143.61	11 %	2984	3316
6	125.31	13 %	2986	3797
7	105.6	16 %	2986	3797
8	86.34	18 %	3800	4321
9	76.89	11 %	3785	4807
10	68	12 %	3786	5435
11	59.62	12 %	3788	6199
12	51.59	13 %	3790	7163
13	43.96	15 %	3789	8385
14	39.68	10 %	3789	9288
15	35.73	10 %	3790	10313
16	32.05	10 %	3791	11493
17	28.7	10 %	3791	12828
18	25.65	11 %	3792	14352
19	22.93	11 %	3792	16054

Table 7. **Reduction schedule No. 2**

Composition: 09G2S+08Kh13				
No. of pass	Thickness, mm	Reduction, %	Width, mm	Length, mm
0	158		2100	2700
1	117.8	25 %	2211	3679
2	105.07	11 %	2356	4125
3	93.64	11 %	4125	2644
4	82.47	12 %	4125	2999
5	71.22	14 %	4125	3000
6	60.97	14 %	3001	5565
7	47.37	22 %	2992	7097
8	37.78	20 %	2995	8890
9	30.41	20 %	2996	11030
10	24.5	19 %	2997	13494
11	20.53	16 %	2999	16319

in direction to side edges and in directions to the front and rear end parts of the billet can be observed for the materials with higher strength (316L and Ni Alloy). Thickness of the clad layer in the center of rolled product is practically constant. More "soft" stainless steel 08Kh13 is characterized by practically uniform shape of the clad layer. Difference by thickness in the edge and central areas makes up to 30 % for Ni Alloy and up to 15 % for 316L steel.

Obtained values of the coefficient ϑ are presented on the **Fig. 10**. The relationship for the composition K60 + 316L is also described by a degree function:

$$\vartheta = 1.076 \cdot \varepsilon_{\ln total}^{0.0174}$$

The coefficient ϑ is equal to 1.091 at the final deformation degree.

As for the composition 09G2S+08Kh13 and reduction schedule No. 2, the coefficient is practically permanent and equal to 0.99; however, its small lowering can be observed in the case of increase of total deformation. The relationship can be described as follows:

$$\vartheta = 0.994 \cdot \varepsilon_{\ln total}^{-0.004}$$

Obtained relationships between the coefficient ϑ and total deformation allow to find the final value of the clad layer thickness. Comparison of these data, which are based on the results of simulation and practical tests, is presented in the **Table 8**.

It is seen from the Table 8 that close values were obtained in simulation and during rolling in industrial conditions; it testifies on sufficient simulation accuracy. The obtained relationship for the composition K60+ Ni Alloy is

$$\vartheta = 1.164 \cdot \varepsilon_{\ln total}^{0.05}$$

It is concluded that the coefficient ϑ for the final value of the total logarithmic deformation is equal to 1.21, what is larger by 11 % than the same parameter for the composition K60+316L.

Conclusions

1. Essential increase of deformation resistance for the nickel alloy was obtained within the temperature range 880-900 °C based on the results of laboratorial experiments and tests on the "Gleeble" unit.

2. The finite element models for rolling of bimetallic steel billet at laboratorial duo 300x250 rolling mill and the industrial plate

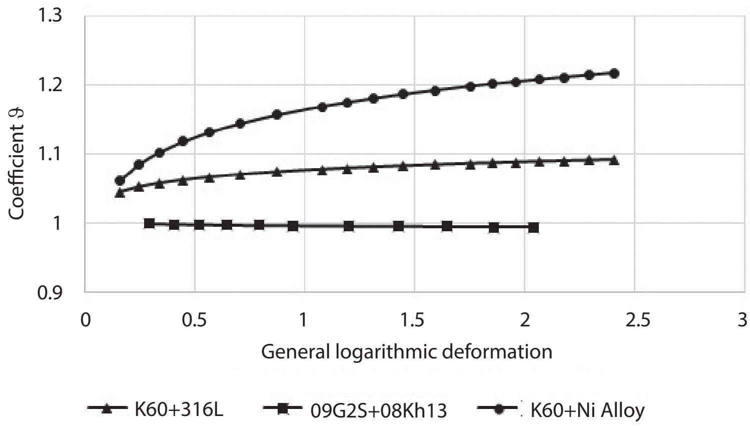

Fig. 10. Relationship between ϑ parameter and general logarithmic deformation for rolling in industrial conditions

Table 8. **Comparison of the final thickness of the clad layer in the cases of simulation and rolling in industrial conditions**			
Composition	Initial thickness of the clad layer, mm	Final calculated thickness of the clad layer, mm	Measured thickness of the clad layer, mm
K60+316L	35	3.44 (center)	3.5-3.7 (center – front end part of strip)
09G2S+08Kh13	40	5.15 (center)	5.1-5.3 (center – front end part of strip)
K60+Ni Alloy	35	3.84 (center)	-

mill were developed for different material combinations of the main and the clad layers.

3. It is shown that 3D model is required to be used for simulation of rolling of bimetallic strips at laboratorial duo 300x250 rolling mill, because the principle of flat deformation is not kept in this case. Such circumstance also determines impossibility of use of laboratorial data about relationship between deformation values of different layers in industrial conditions.

4. It was established on the base of 3D simulation that the clad layer has non-uniform thickness both in the directions of sheet width and length. It is stipulated by the fact that the clad layer can “overflow” from beneath the main flow with less resistance.

5. To evaluate the relationship between deformation of the main and the clad layers, it was suggested to use relation of clad layer relative thickness in the beginning of deformation to clad layer relative thickness in the end of deformation. Relationship between this parameter ϑ and the value of general logarithmic deformation is well describing by a degree function.

6. The obtained values of ϑ for laboratorial rolling (1.65-1.75) are higher than at industrial rolling of slabs, due to absence of flat deformation in strip central part.

7. The conducted work allows to decrease expenses on pilot-industrial rolling tests at the industrial plate mill, owing to reducing the number of rejected sheets on the base of correct choice of the clad layer initial thickness as well as use of the technological parameters obtained during laboratorial rolling tests.

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