Modelling of the sheet forming while 3-roller bending process

G. P. Zhigulev*, Cand. Eng. [1], e-mail: aldebaran2000@yandex.ru;*
M. M. Skripalenko*, Cand. Eng., Associate Prof., Metal Forming Dept.[2], e-mail: mms@misis.ru;*
V. A. Fadeev*, Cand. Eng., Metal Forming Dept.[2], e-mail: fdv_viktor@mail.ru;*
M. N. Skripalenko*, Cand. Eng., Associate Prof., Metal Forming Dept.[2], e-mail: tfsmn@yandex.ru;*
V. N. Danilin*, Cand. Eng., Associate Prof.,Metal Forming Dept.[2], e-mail: danilinvn@yandex.ru*

[1]DKN-T JSC (Moscow, Russia)
[2]National University of Science and Technology "MISiS" (Moscow, Russia)

3-roller bending process was investigated using physical modelling and computer simulation. Main technological parameters influence on the formation of tube billet diameter are present; these main technological parameters are upper roller displacement and distance between axes of bearing rollers. Complete factorial experiment was conducted using bending machine, radius of the produced tube billet was set as response function. Conditions for conducting the complete factorial experiment using bending machine and techniques of tube billet radius estimation by graphical-analytical method are presented. At that least square method and SolidWorks software were applied. Regression equations for calculating tube billet diameter conditionally upper roller displacement and distance between axes of bearing rollers were obtained. Influence of these two factors on tube billet radius formation was demonstrated. Finite element method (FEM) computer simulation of the forming process was done with respect to parameters corresponding to parameters of physical modelling experiment using bending machine. FEM computer simulation was done using QForm software. QForm simulation was realized for elastic-plastic bending in terms of two-dimensional deformation. Point tracking was applied to calculate coordinates of the points of the formed sheet and bending parameters. It allowed estimation of the neutral line location in the formed sheet when bending stage was finished. Presented results of computer simulation are figures with trajectories of the tracked points; figures illustrating changing of distance between tracked points; graph of accumulated strain changing through sheet's thickness. New criterion for neutral line (neutral surface) was proposed for sheet bending process. Results of the research can be effective when exploring Heausler AG bending equipment.
Keywords: bending, forming, rolling, bending parameters, ovalization of the billet's shape, straight weld large diameter tube, neutral line.
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Introduction

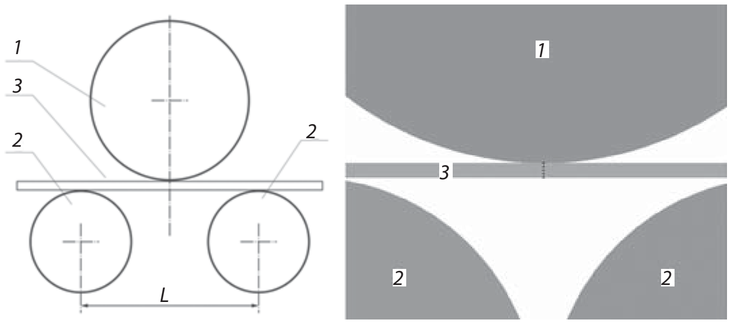
Straight weld large diameter tubes (LDT) are manufactured by different techniques: press forming or forming using bending machine [1-5]. Modern manufacturing lines (of Haeusler AG) include roller forming mill, roller device for bending of edges, welding-assembling mill for preparing of strip for welding, welding section, expander for making the final profile of the tube. All manufacturing schemes include elastic-plastic bending of the billet [6-11]. 3-roller bending process using Haeusler AG equipment with modern automation tools and counter-bending allows manufacturing tubes of 12.5 m length. For that reason, calculation of technological parameters is conducted in terms of two-dimensional deformation.

Quality of LDT is mainly defined by deviation of tube cross section from cylindrical shape (ovalization) and physical-mechanical properties. Influence of properties was not considered in this paper. Ovalization tolerance of LDT is within 3-5 mm range for underwater pipeline according to DNV standard [12]. Despite using expanders [13, 14], specifications for welded tubes always have ovalization tolerances for the cross-section shape. Known solutions [15, 16] which define regimes of tube billet forming when using 3-roller bending mills mostly consider deformation zone structure as symmetrical with application of load to bending roller in the middle of its contact surface and with bearing of billet on lower bearing rollers. However, latest research [17-20] has demonstrated the following. When upper bending roller is replaced without rotation, four-point contact symmetrical deformation zone is formed and separation of billet from the surface of the bending roller. When rotation of the rollers is on at the second stage and when bending is combined with displacement of billet in the deformation zone, three-point asymmetrical deformation zone is formed with displacement of point of load application at the bending roll towards the entrance of the deformation zone. Value of neutral line's length is needed for calculation initial billet's width. Neutral line's length is defined with respect to the radius of the neutral cylindrical surface of the final tube. It is offered to consider neutral line as a line whose shape changes from straight to circle. Deformation is minimal along this line and strain effective is defined by shear strain. Hence, shear strain effective will also be minimal so as accumulated strain. Displacement of neutral line form the middle while bending needs additional research. Authors of [21] think that only shape changes and there is no change of the volume of the particles of the neutral line. There is an assumption that deformation energy is minimal along the neutral line and deformation increment does not occur along the neutral line. Neutral line should be located at the tension zone at 0.25H distance from the lower edge of the billet, where H is billet's thickness. At that neutral line does not coincide with the central line of the billet.

The research objective was investigation of influence of 3-roller bending process deformation regimes on the radius of tube billet and determination of neutral line location using physical modelling and computer simulation.

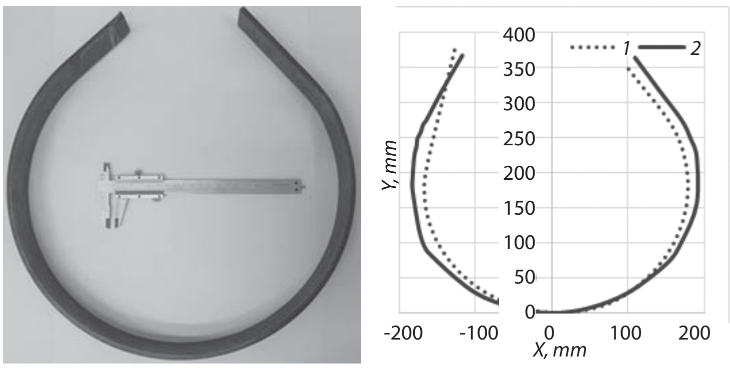
Method of physical modelling

One of the most productive and reliable techniques of forming process research is direct physical modelling [22-25]. Tube billet forming was made using PBT 25 machine [26] of the Metal Forming Department of NUST MISiS. Scheme of rollers location and its computer model with position of tracking points are presented on **Fig. 1**.



a b

Fig. 1. Scheme of location of rollers of PBT 25 machine (a) and QForm computer model (b):
1 – bending roller (R =137.5 mm), *2* – bearing rollers (r = 97.5 mm); *3* – sheet billet



a b

Fig. 2. Photograph of the formed tube billet (a) and inner contour of the tube billet (b):
1 - QForm simulation; *2* - experiment

Experiments were conducted in terms of complete factorial experiment [27]. Two main technological parameters were chosen: displacement of bending roller - Δh and distance between axes of bearing rolls – L. Each factor was varied at two levels. Zero level of factors was 19 mm for Δh and 230 mm for L. Intervals of varying were 3 mm for Δh and 30 mm for L. AISI 1020 steel billet of 6 mm thickness was used for experiments.

Radius of produced tube billet R was chosen as response function. **Fig. 2** presents photograph of one of the formed billets (Fig. 2*a*) and inner contour of billet at parameters Δh=16 mm and L=200 mm obtained on the results of physical modeling experiments and computer simulation.

Radius of the formed tube billet was estimated using graphical-analytical method. Cross-section of the formed tube billet was projected on the coordinate plane. Center of the circle and length of flat sections were detected using coordinates of the points of the profile of the inner surface. Measuring of coordinates was done using caliper.

Radius of circle was measured by caliper after center of circle was detected. Radius was estimated using points coordinates in two ways: radius was calculated using least square method and using SolidWorks menu tools. Radius values are presented in **Table 1**. Numbers of tests correspond to planning matrix (**Table 2**).

Physical modeling results

Tests and statistical processing were done using planning matrix which is presented in table 2. Four tests were conducted by planning matrix and two parallel tests according to techniques of complete factorial experiments. Values Yu1 and Yu2 correspond to results of radius measurement in first and second parallel tests, $\bar{y}$u is radius average value calculated by these two tests. Statistical processing was done because of radius estimation by all used techniques to obtain regression equation.

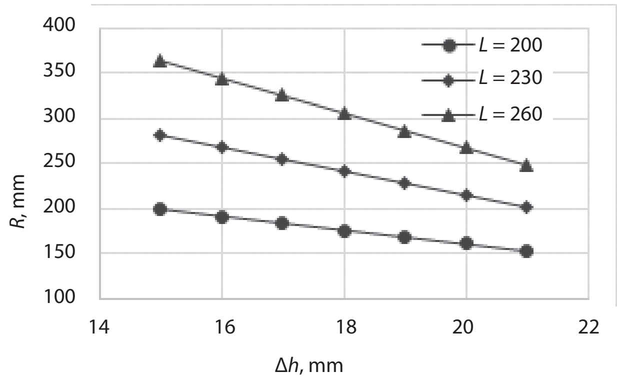
It was established because of statistical processing that the variance uniformity hypothesis for radius values obtained using SolidWorks cannot be accepted. It is because calculated Cochran's criterion exceeded table value of this criterion. Regression equations for radius calculation which were obtained using values detected by graphical-analytical method and least square method appeared to be adequate mathematical models. However, convergence of regression equation radii values using graphical-analytical method with experimental results was 0.33 %. Convergence of regression equation radii values using least square method with experimental results was 3.60 %. Hence, for the graphical-analytical method convergence is better than for least square method. For that reason, regression equation obtained using graphical-analytical method was chosen for further research:

Table 1. **Values of radii detected by different ways**

No. of the test	Δh, mm	L, mm	First set of tests				Second set of tests			
			No. of the billet	Radius R, mm			No. of the billet	Radius R, mm		
				Graphical-analytical method	Least square method	Solid works		Graphical-analytical method	Least square method	Solid works
1	22	260	11	232.5	232.3	236.5	21	231.5	225.3	232.4
2	16	260	12	350	350.9	380	22	343	348.6	341
3	22	200	13	147	149.2	147.25	23	149	151.7	149.21
4	16	200	14	192.5	191.3	190.6	24	193	199	199.96

Table 2. **Planning matrix and results of experiments**

No. of the test	X_0	Δh	L	Δh·L	Graphical-analytical method			Least square method			SolidWorks		
		X_1	X_2	X_1X_2	Radius R, mm			Radius R, mm			Radius R, mm		
					Yu1	Yu2	$\overline{yu}$	Yu1	Yu2	$\overline{yu}$	Yu1	Yu2	$\overline{yu}$
1	1	1	1	1	232.5	231.5	232	232.3	225.3	228.8	236.5	232.4	234.45
2	1	-1	1	-1	350	343	346.5	350.9	348.6	349.75	380.0	341	360.5
3	1	1	-1	-1	147	149	148	149.2	151.7	150.45	147.25	149.21	148.23
4	1	-1	-1	1	192.5	193	192.75	191.3	199	195.15	190.6	199.96	195.28



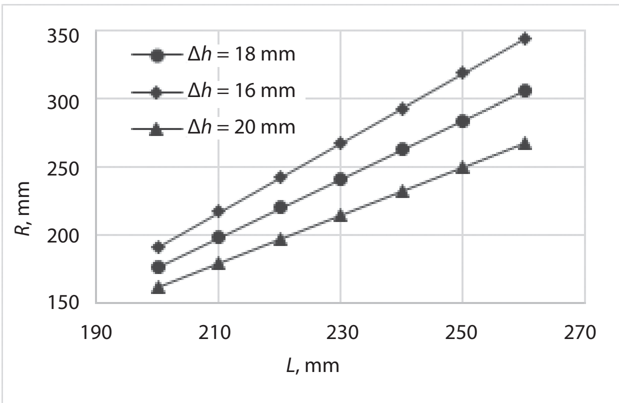


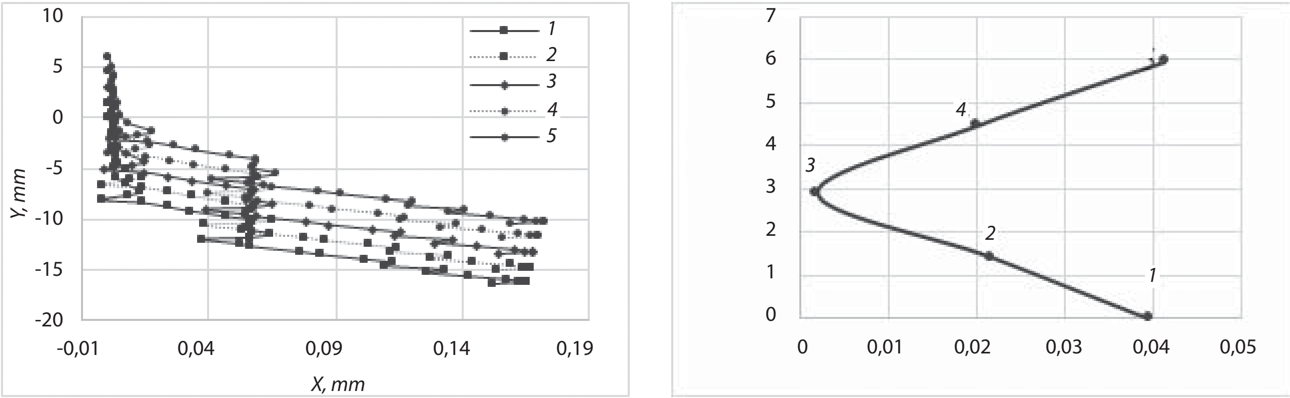
Fig. 3. Dependance of radius R of formed billet from: bending roller displacement Δh at different fixed values of distance between bearing rollers L (*a*); distance between bearing rollers L at different fixed bending rollers displacement values Δh (*b*)

$$R = -820.58 + 31.3\cdot\Delta h + 5.66\cdot L - 0.194\cdot\Delta h\cdot L \quad (1)$$

Graph illustrating variation of tube billet radius with changing of bending roller displacement is presented on **Fig. 3***a*. Graph illustrating variation of tube billet radius with changing of distance between centers of bearing rollers is presented on Fig. 3*b*.

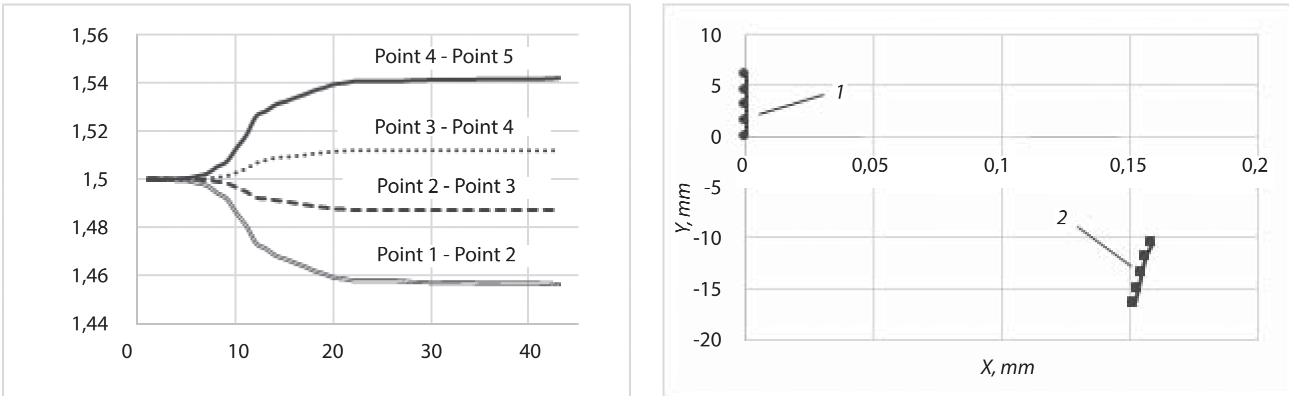
Method of computer simulation

Bending process realized while experimental research was simulated by QForm. Simulation was done for forming stage. Elastic-plastic bending of rectangular billet was investigated in terms of two-dimensional deformation. Sketch was preliminary created using SolidWorks. Sketch contained contours of upper and lower rollers in the form of circles of corresponding radii, equal to radii of rollers of experimental-machine. Contour of billet cross section was also created in the sketch. This contour was rectangle with 1000 mm width and 6 mm height. Created sketch was saved in .dxf format and downloaded into QForm. Billet material was assigned as 1020 (AISI) steel. Upper roller velocity was 2 mm/s vertically downward. Coulomb friction law and 0.8 friction factor value were assigned for setting the contact interaction between rollers and billet. Choosing other friction laws or lower friction factor values in terms of Coulomb friction law did not provide steady bite of billet by rollers. Simulation was conducted without taking heat transfer between billet and rollers into consideration. Boundary condition in the form of finite element mesh adaptation was assigned for the billet. The condition was set for the mesh adaptation: maximum finite element size did not exceed 0.1 mm and simulation was done without remeshing. Boundary condition in the form of finite element mesh adaptation was performed for the whole billet. Boundary condition in the form of finite element mesh adaptation was assigned for all the rollers. At that, maximum finite element size did not exceed 0.1 mm and this limitation



a *b*

Fig. 4. Trajectories of the tracked points (a) and changing of accumulated strain along billet's thickness obtained by QForm simulation (b):
1 – Point 1 (lower edge of the billet); *2* – Point 2 (1.5 mm from the lower edge of the billet); *3* - Point 3 (3.0 mm from the lower edge of the billet); *4* – Point 4 (4.5 mm from the lower edge of the billet); *5* - Point 5 (upper edge of the billet)



a *b*

Fig. 5. Changing of distance between tracked points (a) and their position (b):
1 – before deformation; *2* – after deformation

was performed only for rollers' surface. Billet's temperature was set 20 °C.

Computer simulation results

QForm simulation allowed estimation of strain state of billet's area located under the upper roll. Estimation was done for the stage when upper roller moved vertically downward. Five points with 1.5 mm step between them were taken using point tracking option of QForm (**Fig. 4***b*). Points were numbered as follows: point No. 1 was on the lower edge of the billet, point No. 5 – on the upper edge of the billet, point No. 3 – in the middle of the billet. Points were tracked for the stage when upper roller moved vertically downward. Trajectories of the points are presented on Fig. 4*a*.

Accumulated strain value for each tracking point was calculated. Graph illustrating changing of accumulated strain along billet's thickness is shown on Fig. 4*b*.

Changing of distance between tracked points and their position are shown on **Fig. 5**.

Line was put on the billet while QForm simulation, line was passing through tracked point 3 and was equally distanced from upper and lower edge of the billet. Before bending this line was on the line of billet's symmetry and had 1 m length. When QForm simulation was over, it was established that line has shifted 0.15 mm from the line of symmetry towards tension zone. Length of this line at this stage was calculated. Shape of deformed billet and line in it were saved in .dxf format after QForm simulation was done. Created file was opened using SolidWorks and only layer corresponding to the line was imported. Length of the line was calculated using "Measure" command of the "Evaluate" inset of SolidWorks menu. Length of the line was 1000.016 mm, so it can be accepted as 1 m (length did not change). Hence, measured line represents neutral line passing through point 3 and has minimum of accumulated strain. Neutral line position should be considered while detection of billet width for forming, especially when billet's thickness is more than 20 mm, because neutral line shift in this case will be considerable.

Conclusions

Physical modeling of forming process was done using 3-roller bending machine in terms of complete factorial experiment. Graphical-analytical method application efficiency was shown for formed tube billet radius estimation. Efficiency of this method was shown in comparison with other methods used. Regression equation connecting tube billet radius with upper roller displacement value and distance between bearing rollers axes was obtained. Graphs representing influence of these parameters on the tube billet radius were presented. Computer simulation of the forming process at the values of chosen process parameters Δh=16 mm and L=200 mm revealed that neutral line does not coincide with billet's symmetry line at the bending stage, at that there is 0.15 mm shift of the neutral line towards tension zone. Neutral line length does not change at the bending stage and remains 1 m, at that accumulated strain has minimal value. Minimum accumulated strain criterion can be used for neutral line detection at the bending stage.

Heausler AG 3-roller banding machines are explored in Russia and abroad, including AO Volzhsky Pipe Plant, Zagorsk Pipe Plant. Knowledge concerning deformation zone features while pushing upper roller and forming with rollers rotation allows minimization of shape defects due rational choosing of distance between bearing rollers axes L and upper roller displacement Δh. Regression equation obtained using PBT 25 bending machine (Switzerland) can be applied for calculation of bent profiles radius when they are manufactured from sheet billets using machines of specified type.

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