Study of Different Parameters Which Influence on the Combined Process of Asymmetric Rolling and Plastic Bending of Large Bodies of Rotation

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Abstract*-The main goal of the investigation is to determine key technological parameters, necessary for producing required curvature of sheets up to 4000 mm in width with the required mechanical properties. Investigation into dynamics of the process' main technological parameters allowed to define its three characteristic stages: asymmetric rolling, asymmetric rolling in combination with initial unsettled plastic bending, and asymmetric rolling combined with settled plastic bending. It was found out that the intensity of the deformations changes unevenly, depending on the height of the deformation zone, on all three stages, with its highest value being in the lower part of the sheet, and with the lowest value being in its center. In the second stage, the intensity of the deformation abruptly increases, and a significant asymmetry on the sheet thickness occurs. In the third stage, the non-uniformity of the intensity deformations fields decreases. Similar results can be also observed for stress intensities. Casings on two converters were produced and installed in the oxygen-converter plant. Economic effect from the installation of the developed technology was more than 1 million dollars.

Keywords*- *Asymmetric Rolling; Plastic Bending; Large-size Bodies of Rotations; Curvature; Mathematical Modeling

I. INTRODUCTION

The basic principles of asymmetric rolling are studied and presented extensively in academic literature [1-5]. Many works have studied asymmetric rolling technology by using finite element method (FEM).

Ji et al. [6] investigated deformation mechanics of differential-speed rolling with a high-speed ratio be-tween the top and the bottom rolls by rigid-plastic FEM. Sverdlik et al. [7] has demonstrated that during asymmetric rolling shear strain along the strip cross-section increase more than 9 times in comparison with symmetric rolling. Ji and Park [8] have analyzed various asymmetric rolling processes by the rigid-viscoplastic FEM. The findings of the numerical simulation have revealed that differences in size, rotational speed or friction condition between the top and the bottom rolls can cause asymmetric deformation in the sheet. Shear strain is more severe in the lower layer, where the diameter, rotational speed or friction factor is greater than in the upper layer. Kim et al. [9] has analyzed the effect of speed ratio on the development of shear deformation and texture during differential speed rolling. FEM simulation results have shown that the effective strain accumulated during asymmetric rolling increases with high-speed ratio. Angella et al. [10] has researched the strain distribution developed during asymmetric and symmetric rolling with a large number of passes. FEM results have demonstrated that surface strain effects related to local friction between working rolls and sample surface regions promote an additional deformation leading to a significant contribution at large plastic strain and generate discrepancies between equivalent strain values assessed by continuum theories and those evaluated by FEM models. Saeed Tamimi et al. [11] have investigated the impact of process parameters on the onset and growth of shear strain throughout the thickness of sheet samples by finite element simulations. In accordance with the FEM predictions, the experimental results have shown that the shear strain spread throughout the thickness of sheet samples during asymmetric rolling and developed the shear texture. Gong et al. [12] have investigated the micro-structure and mechanical properties of the twin-roll cast (TRC) Mg–4.5Al–1.0Zn alloy sheets produced by differential speed rolling (DSR). The results are compared with those of the sheet processed by equal speed rolling. It is shown that with the increase of the rolling reduction, the microstructures in the processed sheets become more homogeneous and more refined. These results suggest that, in comparison with conventional casting and rolling, the combined technology of TRC and DSR is a more effective way to process magnesium sheets with enhanced formability after final annealing. Hamad [13] has analyzed the effect of the deformation path on the microstructure, microhardness, and texture evolution of interstitial free steel processed by differential speed rolling method. For this purpose, total height reductions of 50% and 75% were imposed on the samples by a series of differential speed rolling operations with various height reductions per pass (deformation levels) ranging from 10 to 50% under a fixed roll speed ratio of 1:4 for the upper and lower rolls, respectively. Microstructural observations using transmission electron microscopy and electron backscattered diffraction measurements showed that the samples rolled at deformation level of 50% had the finest mean grain size (~ 0.5 μm) compared to the other counterparts; also the samples rolled at deformation level of 50% showed a more uniform microstructure.

This study presents a new technology of the combined process of asymmetric rolling and plastic bending to produce parts of bulky bodies of rotations. Traditionally, machine-building factories produce large-size bodies of rotations, with the help of

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an inefficient and rather costly process, using stamping or sheet-bending machines. These details are designed for usage as casings for various technological aggregates (converters, mixers, scrubbers, steel teeming ladles, etc.). The goal was to develop a cost-effective technology of large-size bodies of rotations production, in the conditions of thick-plate mill.

Results of numerical investigation showed the difficulty and sometimes outright impossibility of producing the required product curvature using only thick plate vertical asymmetric rolling processes. The new operation, which ensures a plate of the required curvature, is needed. Plastic bending, performed with a special unbending roller, located behind the stand, serves as such an operation (Fig. 1) [14-18].

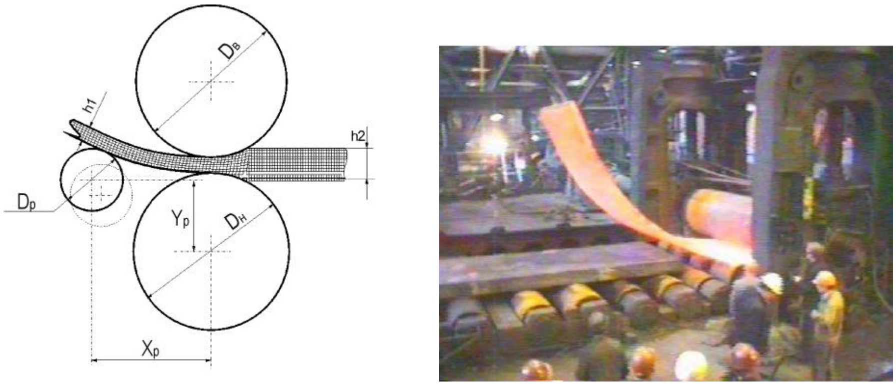

Fig. 1 Combined process of asymmetric rolling and plastic bending

In such conditions, a sheet with far less than required curvature (larger radius) was formed. Then, with said roller, the curvature was increased (by decreasing the radius) to the required value. Such is the combined asymmetric rolling and plastic bending process. In order to analyze it and to develop a corresponding technology, it was necessary to conduct a theoretical and experimental investigation of this process.

II. NUMERICAL INVESTIGATION OF COMBINED ASYMMETRIC ROLLING AND PLASTIC BENDING PROCESS

In mathematical modeling of the tensely deformed condition during combined asymmetric rolling and plastic bending process, finite element analysis was used. The following was used as the input parameters: diameters of working rolls and the unbending roller; thickness of the sheet, on entrance to and on leaving from the deformation zone; sheet width; vertical and horizontal coordinates of the unbending roller. It also were taken into consideration the temperature of the plate before rolling, laws and parameters of friction at contacts of the deformed metal with the rolls and the unbending roller, speed of work rolls rotation and mechanical properties of the material.

As a result of solving the dynamic problem, in each moment of time the following was calculated: radius of roll curvature; fields of stress, of deformation, of deformation speeds, of movements and speeds in the deformation zone; distributions of normal and shearing contact stresses; leverages and torque moments of rolling on work rolls.

The main goal of the investigation was to determine key technological parameters, necessary for producing required curvature of sheets up to 4000 mm in width with the required mechanical properties. These parameters were determined as following: 1) diameter of the unbending roller; 2) vertical and horizontal coordinates of the unbending roller; 3) difference between the diameters of the work rolls; 4) reduction; 5) rolling temperature; 6) rolling speed.

Possible range of initial parameters is dictated by the conditions of plate mill 4500. It is 800...1000 ° for the initial temperature; 0.1...0.3 for friction coefficient; 40.220 mm for plate thickness when entering the deformation zone; 2.12 mm for the absolute reduction; 1160.1250 mm for work roll diameters; 10.23 rotations/minute for speed of work roll rotation; 2000.4000 mm for plate width.

Roller of run-out roller conveyor at the plate mill 4500, with the diameter of 700 mm, was used as the unbending roller. This roller was placed as close as possible to the rolling stand, in order to decrease the length of the sheet's rear end, where no plastic bending takes place. Minimal distance (in the horizontal direction) between the axes of lower working roll and the unbending roller was 1075 mm, because of practical considerations. In the vertical direction, the unbending roller could not be lower than the roller table level, when its axis was placed at the distance of 245 mm from the axis of the lower roll.

Combined process of vertical asymmetric rolling and plastic bending can be separated into three characteristic stages: actual asymmetric rolling (when the front end of the metal doesn't yet touch the unbending roller), asymmetric rolling in combination with initial unsettled plastic bending (when the front end touches the unbending roller), and asymmetric rolling combined with settled plastic bending (after the metal's front end moves beyond the unbending roller).

In the first stage, the front end of the metal follows a path, close to a circle. When touching the roller, the metal starts to bend more. In the third stage, processes of asymmetric rolling and plastic bending occur simultaneously. The third-stage and

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the process as a whole ends after the metal rear end leave the working rolls of the rolling stand. It is clear that the rear end, in the stretch between the exit from the rolls and the area of contact with the unbending roller, will have less than required curvature. It has taken place since this stretch is not subject to the plastic bending. Then the dynamics of changing process parameters depending on the following factors: stages of the process; ratio between the rolls' diameters; absolute reduction was investigated.

Deformation intensity changes non-uniformly, in relation to the deformation zone height, in all three stages (Figs. 2-4). Its highest value occurs near to the lower surface of the sheet, and its lowest value occurs in its center. Deformation increases abruptly in the second stage, with a significant (up to 600%) asymmetry in the sheet thickness. In the third stage, the non-uniformity of the deformation intensities field decreases significantly. The third stage resembles the first in the character of intensity fields distribution. The same observations also apply to the stress intensities (Figs. 5-7).

Speeds field significantly changes from stage to stage (Figs. 8-10). Second-stage witnesses the largest speed non-uniformity (10%) in the sheet thickness.

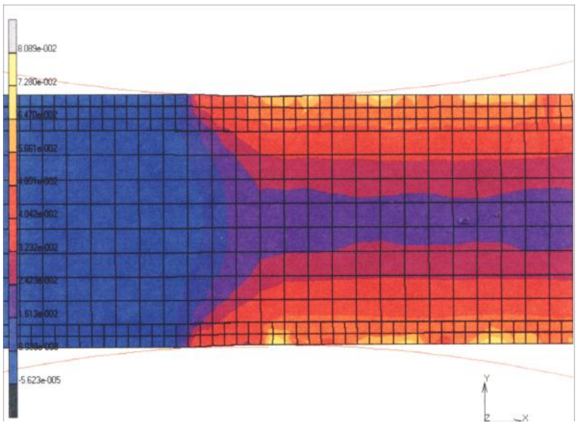

Fig. 2 Deformation intensities field (first stage of the process)

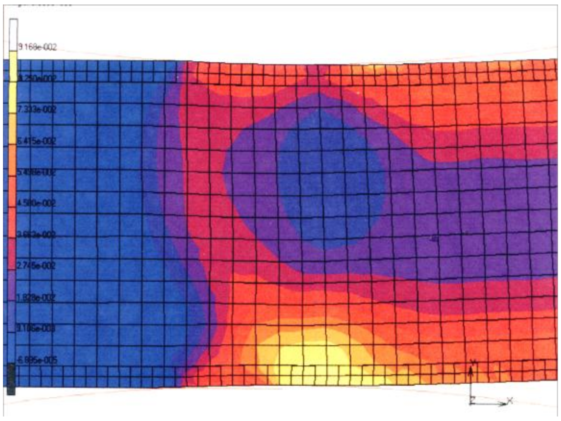

Fig. 3 Deformation intensities field (second stage of the process)

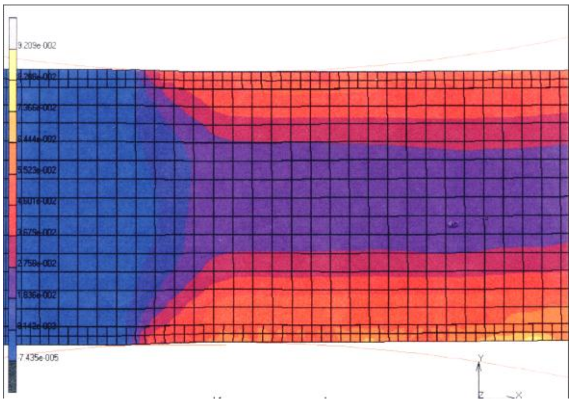

Fig. 4 Deformation intensities field (third stage of the process)

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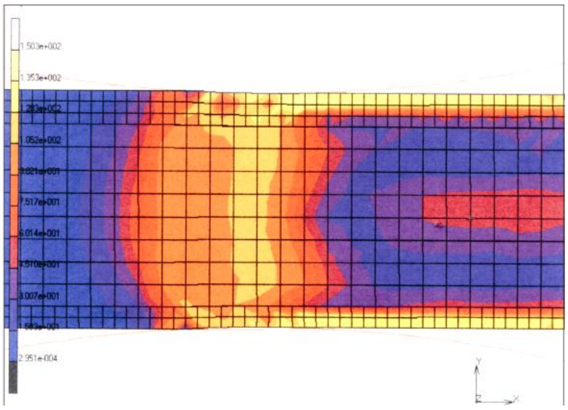

Fig. 5 Stress intensities field (first stage of the process)

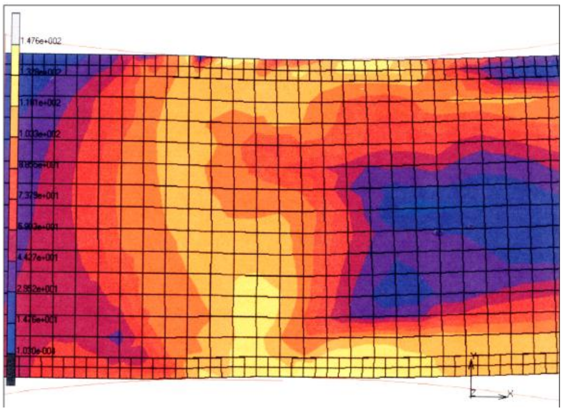

Fig. 6 Stress intensities field (second stage of the process)

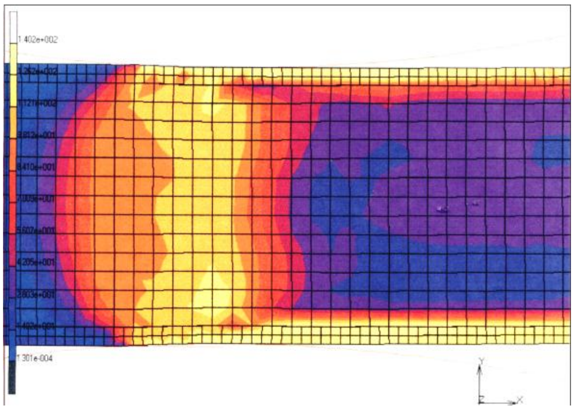

Fig. 7 Stress intensities field (third stage of the process)

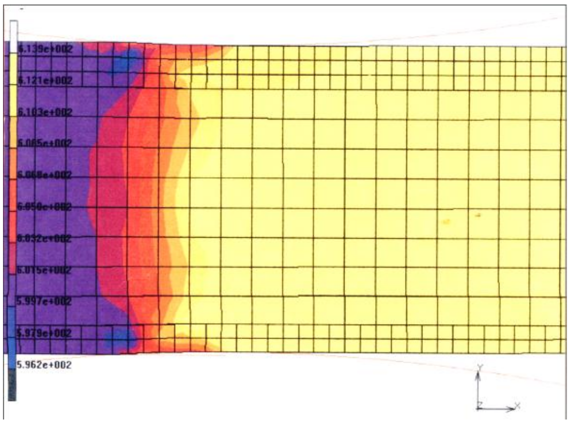

Fig. 8 Horizontal speed component (first stage of the process)

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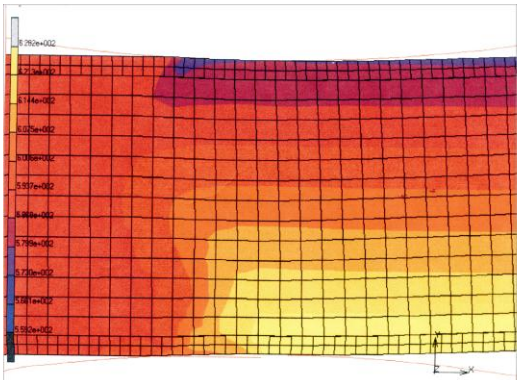

Fig. 9 Horizontal speed component (second stage of the process)

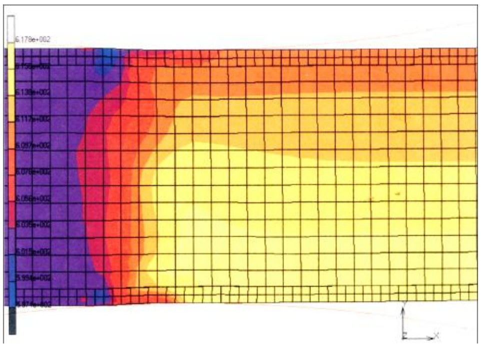

Fig. 10 Horizontal speed component (third stage of the process)

Resulting friction forces on the rolls can change direction during the process. In the first stage, at the contact with the lower roll, leg area prevails, whereas at the contact with the upper roll, outstripping area prevails. All this leads to a difference between roll torque moments on upper and lower rolls. As a rule, the torque in the lower roll is higher than in the upper one. After the front end of the sheet touches the unbending roller (second stage) the distribution of friction areas at the roll contacts abrupt changes. Out-stripping area in the upper roll disappears while it increases in length in the lower roll. In the third stage of the process, the friction difference on contacts with the upper and lower rolls decreases. Asymmetry of friction areas on contacts leads to a *skewing*, of roll torque moments in the rolls: in the first stage of the process it is larger on the lower roll. At the beginning of the second stage the moment in the upper roll abruptly increases, while decreasing on the lower roll, analogous to an impulsive blow. Fig. 11 demonstrates the relative values of roll moments in percentage of roll moment during a symmetrical process.

A theoretical investigation with the help of computing experiments was conducted with three different ratios between the upper and the lower working rolls – 1210/1215, 1200/1220 and 1200/1230 mm and two absolute reductions – 2 and 4 mm (Table 1). Increasing the difference between the diameters leads to a significant redistribution of roll moments in working rolls (Figs. 11-13 and Figs. 14-16). So, in the first variant, the relative value of the moment in the lower roll is 0.78, while it is 0.2 on the upper roll; in the second variant it is 1.35 on the lower roll and a negative value of -0.25 on the upper one; in the third variant it is 1.6 and a negative value of - 0.6 correspondingly. In the second, the riskiest, stage increase of the difference between the diameters does not lead to a significant redistribution of roll moments. With the absolute reduction of 2 mm, the value of the relative moment in the upper roll abruptly increases and, in all cases, equals 1.5 – 1.6, and, in the lower roll, adopts a negative value of - (0,3 – 0,4). Similar results are observed for the reduction of 4 mm. On the third stage of the combined process, a significant difference between the moment distributions is observed in the first and two other cases. With the working roll diameter difference of 5 mm, the moment on the upper roll is larger, while with the differences of 20 mm and 30 mm, the moment on the upper roll is lower.

TABLE 1 PROCESS PARAMETERS

No.	Working roll diameter, mm		Sheet thickness, mm	
	upper	**lower**	**before rolling**	**after rolling**
1.	1210	1215	102	100
2.	1200	1220	102	100
3.	1200	1230	102	100
4.	1210	1215	104	100
5.	1200	1220	104	100
6.	1200	1230	104	100

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Speed asymmetry in the sheet thickness increases in the first stages of the process, as the ratio of the roll diameter decreases. In the upper part of the sheet, the speeds are less than in the lower one. In the second and third stages of the process change in roll diameter ratios do not lead to a significant change of the speeds field.

Increase of the reduction does not change the character of stress and deformation intensities field distribution. Only the absolute values of these parameters increase.

With the decrease of absolute reduction, the length of a zone of sheet-rolls contact and absolute values of friction in the contact zone, also decrease. As a result of this, the values of torque moments in rolls also decrease (see Figs. 11-16).

Accordingly, a conclusion can be made, that in order to prevent equipment breaking, the combined process of vertically asymmetric rolling and plastic bending must be conducted with the minimum possible reduction. Use of diameter difference of working rolls more than 25 mm does not appear to be reasonable.

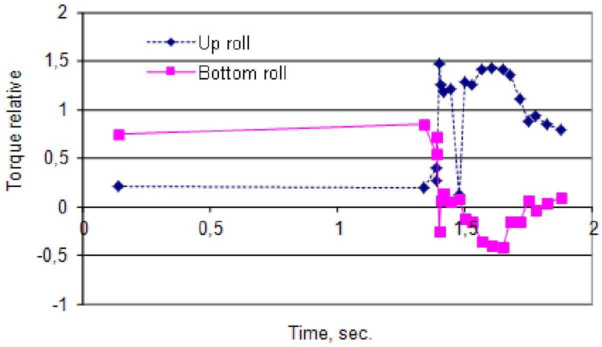

Fig. 11 Roll torque moment (var. 1)

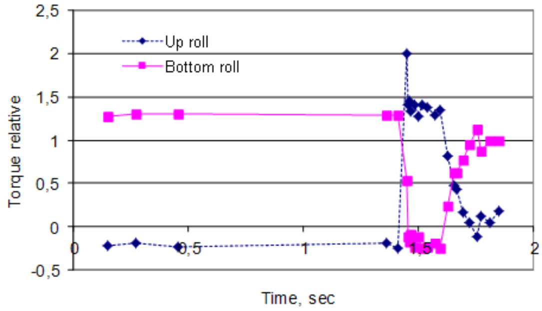

Fig. 12 Roll torque moment (var. 2)

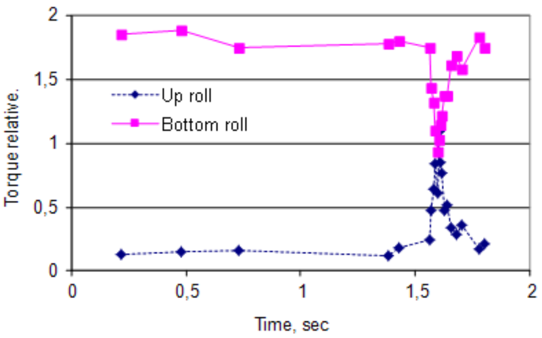

Fig. 13 Roll torque moment (var. 3)

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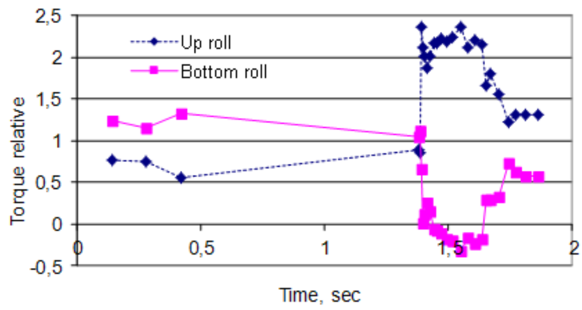

Fig. 14 Roll torque moment (var. 4)

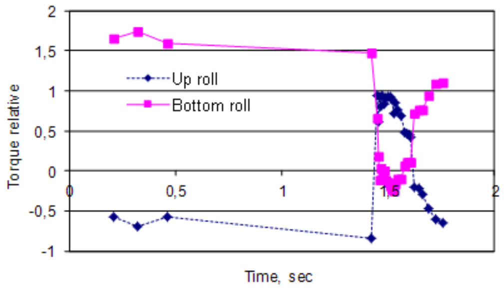

Fig. 15 Roll torque moment (var. 5)

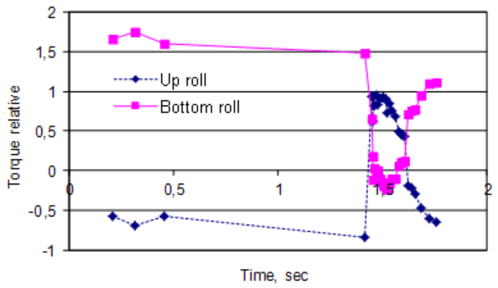

Fig. 16 Roll torque moment (var. 6)

The investigation has shown that after decreasing the metal temperature, the bodies of rotations details' curvature, in the stage of asymmetric rolling, with the working rolls diameters ratio of 0.989…0.995 (diameter difference of 5…12 mm) decreases, but increases with the ratio of 0.975…0.994 (13…30 mm) (Fig. 17). Therefore, if the working rolls diameter difference is low, in order to increase the sheet curvature, the temperature needs to be increased somewhat, but if the diameter difference is low, the temperature needs to be decreased.

Numerical investigation has shown that change of semi-finished rolled product in the range of 800-900 °with the combined process of large-scale bodies of rotations asymmetric rolling and plastic binding does not lead to any significant change in the rolled metal's curvature.

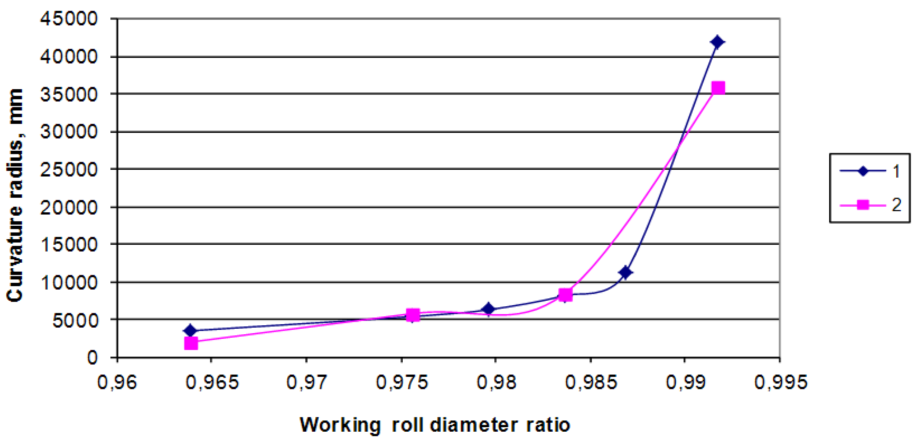

Fig. 17 Influence of work roll diameter ratio and the rolling temperature on the curvature of the sheet 100 mm in thickness with the absolute reduction of 4 mm. 1 - Temperature of 800 °; 2 - Temperature of 900 °

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Numerical investigation had shown that shield curvature is practically independent of rotation speed. Therefore, it would be rational to conduct the rolling on the minimal speed possible, in order to prevent equipment damage in the second stage of the process.

It is proposed to produce large-scale bodies of rotations with the help of the combined process of vertical asymmetric rolling and plastic bending at plate mill 4500 [14-18]. The following values of technological parameters are defined for this process [3, 4]:

- product - body of rotations detail, defined as segment of a cylinder from low-alloyed steel, with angular dimension of 45-60 degrees, thickness of 40-120 mm, width up to 4300 mm, length up to 5000 mm, with the curvature radius of 1850 to 5000 mm;
- heating of semi-finished rolled product - in heating plate mill ovens, with placement in the oven, up to the temperature 900 – 950-°, with the required exposure of 0.5-1 hours, depending on the thickness of the semi-finished product;
- diameter of the unbending roller is 700 mm, first roller of the run-out roller conveyor is used as the unbending roller, with its placement in specially prepared cassettes with laying under the roller conveyor;
- difference of diameters between upper and lower working rolls – from 3 mm up to 25 mm;
- horizontal distance between the axes of lower working roll and the unbending roller is 1075 mm;
- horizontal distance between the axes of lower working roll and the unbending roller is determined by the (4.2) formula, depending on the thickness and the required curvature of the sheet;
- reduction – from 2 up to 12 mm, depending on the sheet thickness and width and the difference between the working rolls' diameters;
- rolling temperature is 820 – 900-°;
- rolling speed is the minimal possible, threading (no more than 10 rotations per minute).

The goal of industrial trial was the testing of the proposed technology of large-scale bodies of rotations production, and also an investigation into the mechanical properties of metalware produced as a result of mechanical properties deformation.

Pilot products were manufactured, with the thickness of 70 to 100 mm. The placement of the unbending roller was specified.

As a result, the following technological parameters of large-scale bodies of rotations from low-alloy steel were taken into consideration. They depend on the required sheet curvature: difference of working rolls' diameters from 5 to 30 mm, reduction – from 2 mm (sheet thickness of 40 mm, width of 3000-4000 mm, difference in the rolls' diameters of 10-30 mm) up to 12 mm (sheet thickness of 220 mm, width of less than 3000 mm, difference in rolls' diameters – 5-10 mm), placement coordinates of the unbending roller, speed of rolling – up to 10 rotations/minute, temperature of semi-finished rolled product heating of 900 °C.

Casings on two converters were produced and installed in the oxygen-converter plant. Economic effect from the installation of the developed technology was more than 1 million dollars.

III. CONCLUSIONS

Investigation into dynamics of the process' main technological parameters made it possible to define its three characteristic stages: asymmetric rolling, asymmetric rolling in combination with initial unsettled plastic bending, and asymmetric rolling combined with settled plastic bending.

It was found out that the intensity of the deformations changes unevenly, depending on the height of the deformation zone, on all three stages, with its highest value being in the lower part of the sheet, and with the lowest value being in its center. In the second stage, the intensity of the deformation abruptly increases, and a significant asymmetry on the sheet thickness occurs. In the third stage, the non-uniformity of the intensity deformations fields decreases. Similar results can be also observed for stress intensities.

It was shown that the second stage, in which the rolling moment on the upper roll of the stand significantly increases, is the riskiest for the equipment, and can lead to its damage.

The following technological parameters were defined for production of large-scale bodies of rotations from low-alloy steel, depending on the required sheet curvature: difference of working rolls' diameters from 5 to 30 mm, reduction – from 2 mm (sheet thickness of 40 mm, width of 3000-4000 mm, difference in the rolls' diameters of 10-30 mm) up to 12 mm (sheet thickness of 220 mm, width of less than 3000 mm, difference in rolls' diameters – 5-10 mm), placement coordinates of the unbending roller, speed of rolling – up to 10 rotations/minute, temperature of semi-finished rolled product heating of 900-950 °.

Two converter casings were produced according to the proposed technology, were installed and are being exploited. Resulting from the above mentioned the economic effect was more than one million dollars.

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