Comparison of stress-strain behavior during helical rolling process with various deformation regimes obtained by mathematical simulation in DEFORM-3D software package

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Abstract. In this study, mathematical models of helical rolling under various deformation regimes were built using the Deform-3D software package. Stress-strain behavior after all studied regimes were compared in dependence with technological rolling parameters and geometrical characteristics of helical rolls. Obtained results defined that helical rolling provides appearance of macroshear deformation in transverse and longwise direction of workpiece and high value of strain intensity defines both during rolling in helical rolls and subsequent flattening. Appearance of multidirectional macroshear deformation seems to provide the increase of technological plasticity, additional melting of cast macrostructure, reduction of transverse anisotropy and decrease the energy-power parameters of longitudinal rolling.

1. Introduction

Today, more than 70 % of the steel are produced by lengthwise rolling. The main disadvantage of lengthwise rolling consists in unidirectional influence of deformation that leads to anisotropy of mechanical and functional properties. Deformation degree is not always enough for refinement of cast structure and obtaining of required strength and toughness, especially for production of plate steel. Also, it is well-known that after lengthwise rolling such structural defects may simply appear as the rolling texture and the streakiness of nonmetallic inclusions [1-4]. At the Baikov Institute of Metallurgy and Materials Science (IMET RAS) the new method of lengthwise rolling – rolling in helical rolls, that allows eliminating the main disadvantages of lengthwise rolling, had been designed and developed. The obtained theoretical and experimental results confirm appearance of macroshear deformation, better structure refinement and a decrease in the energy-force parameters of rolling [5-7]. However the metal flow and main features of deformation process during helical rolling are insufficiently studied. Finite element analyses method is widely used in order to analyze stress-strain behavior during metal forming process [8-10]. Therefore in this work investigation of stress-strain behavior during the helical rolling depending on the technological rolling parameters and geometrical characteristics of helical rolls using mathematical simulation in Deform-3D software package was studied.

2. Experimental procedure
The mathematical simulation of lengthwise rolling in helical rolls was performed by the Deform-3D software package that based on the finite element analyses method. Schematic representation of a helical roll is shown in fig. 1. A helical roll has a screw surface formed by a helicoid with a rounded vertex. 3-D models of helical rolls were developed by the Solid Works software package (fig.2). Geometrical parameters of constructed models are shown in table 1. These geometrical parameters were chosen correspondingly to the rolls of two rolling mills, existing in the production centre of IMET RAS in order to provide possibility of future physical experiments. The geometrical shape of the helical roll from the Solid Works was imported to the Deform-3D in the form of a rigid (undeformed) tool. As the model materials, AISI 304 steel was chosen. For all studies mathematical models following experimental parameters were used: the friction coefficient on the contact surface was 0.3; the temperature of the initial steel billet was 1050 °C; arbitrary mesh was generated with 160000 finite elements with a minimum size of 1 mm; the rolling speed was 4 m/min; the initial billet sizes was 5 × 150 × 300 mm for rolls with a diameter of 110 mm and 20 × 150 × 300 mm – with a diameter of 320 mm. The penetration depth of helicoid was 1.25 for a roll with a diameter of 110 mm and 5.0 for a roll with a diameter of 320 mm that equal to 50 % of relative strain of workpieces in sections between the ridges of the helicoid for both roll diameters. The relative strain after flattening of helicoidally rolled workpieces and after simple lengthwise rolling was also 50 %.

![Figure 1. Schematic representation of helical rolls](image)

**Figure 1.** Schematic representation of helical rolls: D – roll diameter between two ridges; L – roll length; s – height difference between ridges and valleys; R₁ and R₂ – bending radiuses of ridges and valleys; α – angle of helicoid entrance towards the roll axis; m – distance between two near ridges; A – distance between two ridges of one helicoid line.

| D, mm | α, ° | D, mm | Number of helicoid entries (N) | S/2, mm | R₁, R₂, mm | A, mm | m, mm |
|-------|------|-------|-----------------------------|---------|-------------|-------|-------|
| 320   | 45   | 300   | 16                          | 10      | 10          | 300   | 20    |
| 110   | 45   | 340   | 5                           | 5       | 10          | 80    | 20    |
The modelling conditions were changed in accordance with the aim to compare the stress-strain behaviour during helical rolling with different diameters of rolls. After simulation, stresses-strain intensities and energy-power parameter of rolling were obtained and analysed. The adequacy of the mathematical model of helical rolling was previously examined by the physical experiment in [7].

3. Results and discussion

3.1 Helical rolling

The value of strain intensity is proportional to the second invariant of the finite strain tensor, which characterizes the cumulative strain at a certain material point in rolling. Distribution of strain intensity (effective strain $\varepsilon_{eff}$), obtained after simulation of rolling in helical rolls with a diameter of 110 and 320 mm, are shown in figure 3. After rolling in helical rolls with a diameter of 110 mm strain intensity on the top surface of the workpiece is formed in the figure of regular network of remarkable peaks in the point of contact between the workpiece and ridges of both top and bottom helical rolls. For rolls with a diameter of 320 mm influence of bottom roll couldn’t be defined by distribution of strain intensity on the top surface: there are no noticeable regular peaks of stress intensity in comparison with the diameter of 110 mm. Distribution of effective strain in this case is formed in the figure of lines, rotated at the angle of helicoid entrance towards the roll axis, and distributed more evenly over the length of the grooves. Cross section of deformed workpiece shows that in the transverse and longitudinal directions the deformed regions represent a regular network surrounding undeformed (unhardened) metal layers, but for rolls with a diameter of 320 mm the region without deformation are considerably smaller: for rolls with a diameter of 110 mm this areas covers more than 70 % of the workpiece. It means that deformation of thick sheets is more effective for better strain intensity distribution in comparison with thin sheets, because for the same value of relative strain (50 % in the place of heliacal ridges intersection of top and bottom rolls) the distribution of effective strain is more advantageous.

The stresses intensity developed in the workpiece during deformation processes determine the quality of structure refinement. The strong nonuniformity of the stress distribution in the workpiece is related to the specified discrepancy between the tool sizes and the geometrical parameters of the workpiece in its cross section and along its length. Distribution of stress intensity (effective stress $\sigma_{eff}$), obtained after simulation of rolling in helical rolls with a diameter of 110 and 320 mm, are shown in figure 4. On the top surface of the workpiece the maximum value of effective stress is observed in the
grooves formed after the contact of the workpiece and ridges of the roll. For rolls with a diameter of 320 mm the length of maxim effective stress area is much larger. The cross section of the workpiece shows the almost all part of the deformation zone is captured by the stress both for the two rolls diameters. Therefore, zones with lack of height reduction are also involved in the deformation process and stress intensity distributed both over the height and the width of the workpiece with and completely fill the deformation zone with the maximum value in the grooves. It means that the maximum effective stresses are operative across the entire billet depth and that the material in the transverse direction, i.e., over the entire cross section surface, is in a stressed state. The periodicity of effective stresses repeats the periodicity of the roll profile. The stress intensity fields caused by rolling propagates far from the geometric and true deformation zones and decreases slightly with the increase of distances from the groves in width, height, and length.

![Figure 3](image3.png)

**Figure 3.** Distribution of strain intensity after rolling in helical rolls with a diameter of 110 (a) and 320 (b) mm.

![Figure 4](image4.png)

**Figure 4.** Distribution of stress intensity after rolling in helical rolls with a diameter of 110 (a) and 320 (b) mm.

### 3.2 Flattening of helically rolled workpiece

Distribution of stress intensity (effective stress $\sigma_{\text{eff}}$), obtained after simulation of flattening of previously rolled in helical rolls workpiece, are shown in figure 5. The stress intensity on the top surface of the workpiece and in the cross section has irregular profile of maximum value dispersion.
for rolls with a diameter of 110 mm. However the stress intensity is also covering the whole volume of the workpiece and distributes far from the geometric and true deformation zones. The stress intensity for rolls with a diameter of 320 mm propagates considerably uniform in all directions and geometrical shape of the obtained sheet has better quality. According to these facts, relatively high strain rate may be applied only for thick sheets. The deformation rate for the thin sheet should be decreased because of the uninform distribution of the stress intensity and irregular profile of sheet after flattening.

Figure 5. Distribution of stress intensity after flattening of workpiece rolled in helical rolls with a diameter of 110 (a) and 320 (b) mm

3.3 Comparison of energy force parameters
The energy force parameters of all investigated regimes of rolling are shown in table 2. The value of rolling force both after rolling in helical rolls and flattening is smaller than after standard lengthwise rolling with the same relative deformation rate. The same tendency remains for the value of the rolling torque and the normal pressure.

| Table 2. Energy force parameters after rolling with various regimes. |
|---|---|---|---|---|---|---|---|
| | D, mm | h₀, mm | Ɛ, % | Helical penetration depth, mm | Strain intensity (max) | Stress intensity (max) | M, mN/mm | F, kN | Pₙ, MPa |
| Rolling in helical | 110 | 5 | 50.0 | 1.25 | 0.6 | 160 | 0.29 | 3.5 | 3410 |
| | 320 | 20 | 50.0* | 5 | 4.3 | 348 | 12.9 | 9.0 | 3600 |
| | 320 | 40 | 52.5* | 10.5 | 3.0 | 290 | 34.7 | 71.3 | 2200 |
| | 110 | 2.5-5 | 50.0 | - | 6.9 | 120 | 6.3 | 41.6 | 3700 |
| Flattening | 320 | 10-20 | 50.0 | - | 6.7 | 239 | 12.6 | 40.5 | 2900 |
| | 320 | 19-40 | 52.5 | - | 9.7 | 329 | 11.4 | 95.0 | 4900 |
| | 110 | 5 | 50.0 | - | 6.9 | 120 | 16.3 | 52.0 | 7400 |
| Lengthwise rolling | 320 | 20 | 50.0 | - | 10.2 | 432 | 47.5 | 56.9 | 11700 |
| | 320 | 40 | 52.5 | - | 12.0 | 293 | 64.8 | 123.6 | 16600 |

* Relative strain value of workpieces section located between the ridges of the helicoid
The value of the strain and strain intensities is considerably smaller after rolling in helical rolls and slightly smaller after flattening of previously rolled in helical rolls workpiece in comparison with the standard lengthwise rolling, but appearance of stress intensities in the whole volume of the workpiece both in transverse and longitudinal directions provide the multidirectional deformation that is extremely important for better structure evolution during the deformation process and improvement of mechanical and functional properties.

4. Summary
Mathematical models of rolling in helical rolls were built using the Deform-3D software package in order to compare the stress-strain behaviour during helical rolling with different diameters of rolls. Obtained results defined that helical rolling provides appearance of macroshear deformation in transverse and longwise direction of workpiece and high value of strain intensity defines both during rolling in helical rolls and subsequent flattening. Deformation of thick sheets is more effective for better strain intensity distribution in comparison with thin sheets. The stress intensity fields caused by rolling propagates far from the geometric and true deformation zones and decreases slightly with the increase of distances from the groves in width, height, and length for both rolls diameters. Appearance of stress intensities in the whole volume of the workpiece both in transverse and longitudinal directions provide the multidirectional deformation that is extremely important for better structure evolution during the deformation process and improvement of mechanical and functional properties. The value of rolling force both after rolling in helical rolls and flattening is smaller than after standard lengthwise rolling with the same relative deformation rate. According to this fact rolling in helical rolls seems to provide the increase of technological plasticity, additional melting of cast macrostructure, reduction of transverse anisotropy and decrease the energy-power parameters of longitudinal rolling.

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